THE UNIVERSITY OF ALBERTA

CLIMATIC FLUCTUATIONS IN TRINIDAD, WEST INDIES, 1921-66

by

© Orman Granger

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ABSTRACT

The climate of Trinidad in the period 1921-1966 has been investigated for evidence of fluctuations. Pressure, temperature and precipitation are the main climatic elements examined. Statistical methods are employed to test the significance of fluctuations; among these methods are cumulative means, percentual deviations from means, comparison of means of different periods and variance spectrum analysis. The variability of, and oscillations in precipitation are also examined and effects of climatic fluctuations on the water balance are investigated. The extent to which these fluctuations may be reflected in or confirmed by tree core samples is explored.

The results of the analyses indicate that the climate of Trinidad over the past forty-six years has not remained static, but that significant fluctuations have occurred. These fluctuations are not identical at all stations analysed, but there are very close similarities. Fluctuations of irregular lengths have occurred in the temperature of the island, and the period under investigation has been dominated by an increase in temperature between 1933 and 1958, and a decrease thereafter. The overall temperature increased by about 4.8°F. during the period of warming and decreased by about 3°F. during the period of cooling. There have also been fluctuations

of mean sea-level pressure with an average period of eight to ten years. The greatest decrease in this element occurred after 1958.

The analyses of the rainfall data show that fluctuations of an average length of about eight to ten years have occurred, and that since 1957 there has been a tendency towards increased aridity at all stations examined. Some of these fluctuations are statistically significant when compared with one another, but become relatively insignificant when compared with the whole period. The decrease after 1957 is statistically significant at all stations analysed. Further, variance spectrum analyses of annual and dry season precipitation data have isolated oscillations of 5 and 6.6 years at most stations except one, (St. Madeleine) where an oscillatory period of 2.5 years seems to be predominant.

Water balances calculated by the Thornthwaite method, and dendrochronologic evidence corroborate the fluctuations and oscillations in precipitation. The deficits and surpluses in moisture show oscillatory periods similar to those shown by the variance spectrum analysis. Tree-ring samples taken in the island verify some of the fluctuations in precipitation although the tree-ring records did not span the whole period under review.

The study points out the implications of these climatic fluctuations for the water supply requirements of the island, and recommends that continuing research into climatic fluctuations might profitably be on a wider regional basis.

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Water balances calculated by the Thornthwaite method, and predominantly precipitation, determine the fluctuations and oscillations in precipitation. The deficits and surpluses in moisture show oscillatory periods similar to those shown by the variance spectrum analysis. Tree-ring samples taken on the island verify some of the fluctuations in precipitation although the tree-ring records did not span the whole period under review.

The study points out the implications of these climatic fluctuations for the water supply requirements of the island, and suggests that statistically forecast long-term climatic fluctuations might profitably be on a wider research basis.

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CHAPTER I

INTRODUCTION

Over the past three decades, an increased awareness of the variability of climate has led to numerous studies of climatic fluctuations during the period of instrumental meteorological records. Despite the fact that many of these studies are based on different materials, different periods, and different methods, it is possible to draw certain tentative conclusions from them. Climate is varying continually and seemingly randomly, because of endogenous atmospheric processes of which the fluctuations that produced the ice ages are long term spectacular manifestations.

In 1953, the World Meteorological Organization saw fit to incorporate this inherently dynamic aspect of climate into a redefinition of climatology. It described it as

> "the statistical collation and study of observed elements or derived parameters of the atmosphere, particularly in relation to the physical and dynamical explanation or interpretation either of the contemporary climate patterns with their anomalous fluctuations or of the long term climatic changes and trends." (Gordon, 1953)

There seems little doubt that from the end of the last century to date, there have been significant changes in temperature, rainfall and atmospheric flow patterns. Indeed, it is possible to account for the whole geographic distribution of temperature and rainfall changes (apart of

course, from micro-scale and local changes due to urbanization, afforestation, over-cropping, irrigation, etc.) in terms of changes in the general circulation. The findings indicate that the primary effect of causative factors may be hidden in, or quite distorted by, the resulting effects brought about by the modifications of the general circulation through the distribution of land and sea. Sutcliffe (1960) has suggested that it is quite probable that the atmosphere has the inherent ability with its non-linear processes to bring about changes of itself, and far too little weight seems to be given to the built-in variability of climate. Even though some of the fundamental causes of this variability have been correctly identified in various periodicities, there remains a great mass of interacting phenomena. Until all of them are identified, these must be considered as producing random variations.

So far, there has been a vast amount of research done on climatic fluctuations; however, the emphasis has been on fluctuations in middle and high latitude regions which have accumulated the longest series of instrumental data. The tropical regions still remain to be intensely investigated. One of the drawbacks usually seized upon to justify the paucity of studies is the unavailability of sufficiently long series of data. With respect to length of data series, it must be pointed out that knowledge of climate is gathered, transmitted, analysed and learned in

numerical form to a greater degree than is true of most other aspects of the physical environment. Furthermore, it is also true of most aspects of atmospheric behaviour that the data fall under, or are approximated by the Gaussian distribution curve. Thus, the arithmetic mean, and the median are useful indicators of its central tendency. Also, in the humid-tropical environment means are stabilized by periods of record short in comparison with those required in higher latitudes. It follows that the predictive value of the climatic record, in what-ever form it is presented--means, frequencies or extremes--is optimal in the humid-tropical environment, and data availability in terms of the length of records is not perhaps the impediment to climatic studies it is made out to be.

It is well known that variations on the scale of a few weeks superimposed on the annual cycle certainly exist, and extraneous causes need not be looked for, but there are also the variations in seasonal weather from year to year. From the internal evidence, especially the large magnitude of the year to year variations, and the relatively small magnitude of any likely extraneous disturbances, it can be inferred that the year to year variations are indeed built-in characteristics of the system. Whether this line of reasoning can be validly applied to long term changes and trends is quite uncertain. It is perhaps true that each phenomenon follows as the logical result of interaction in obedience to

fundamental physical laws. Inability to see the system as a whole, and ignorance of the operations of the mechanisms of change confer an apparent randomness, and an unusual and enigmatic character on climatic fluctuations.

It is now generally accepted that the most striking feature of climatic fluctuations during the past century has been a warming in many parts of the world since 1850 until a decade or two ago, when, in some places, there appears to be a levelling off or a fall in temperature. Labrijn (1945) has shown that until 1945 there was a general rise in winter mean temperature in the Netherlands from about 1790 onwards and a slow increase in summer mean temperature from about 1800 until the end of the nineteenth century. Thereafter there was a decrease until about 1920 followed by another rise. In Iceland, Eythorsson (1949) found a steady rise in annual temperature of about 1.1°C. from approximately 1916-25 to 1926-35, while Hesselberg and Birkeland (1956) and Hesselberg and Johannessen (1958) showed that there was a rapid rise of temperature at Norwegian stations in 1917-22, continuing at a slower rate (1°C.) thereafter, reaching a peak in 1930, and showing a reversal of the trend in 1940-50. Rubinstein (1956), in a detailed study of climatic changes in the U.S.S.R. during the thirty to forty years before 1950-55, found a warming trend most noticeable in the winter months. This trend culminated in the 1930's. In a study of temperature trends in Canada up to 1952, Longley (1953) found that the 1880's

was cold with a minimum in 1878-80 and that warming has occurred in all districts since then. He also found that the fluctuations from about 1900 onwards were by no means the same in all districts, and that there were minor fluctuations varying in space and time. For the Middle-East, Rosenan (1960) reported that annual temperature showed a minimum in the decades 1890-1910, a rise of .5°C. to 1°C. in 1900-30 followed by a drop in the 40's and a rise in the 50's. Pramanik and Jagannathan (1954) found no general tendency for an increase or decrease in maximum or minimum temperatures at any station in India, but they indicated that the data for some stations suggested a "cycle" of 30-40 years.

So far, most of the studies seem to indicate that the fluctuations were most pronounced in the middle, high and polar latitudes of the northern hemisphere, apparently negative in the polar latitudes of the southern hemisphere and relatively insignificant in the tropics except in Australia and South America where an increase has been shown. Apart from the Indian studies, the only other tropical studies of which this writer is aware are those of Dubief for North Africa (1960) and De Boer and Euwe (1949) for Indonesia. The former maintains that as far as temperature is concerned there may have been slight changes in the area in the last fifty years, although this is debatable. The latter drew attention to a fluctuating but almost continuous increase in the value of the mean annual temperature from 1866 (25.9°C.)

onwards (27.0°C. in 1940). At about 1941 there was a discontinuity in the temperature rise. Schmidt-Ten Hoopen and Schmidt (1951) also indicate that this discontinuity was due to a decrease in the values for January to April beginning about 1910 and reaching a peak in 1921.

Studied in detail, the findings of various workers in respect of temperature fluctuations do not present a simple picture by any means. In trying to fit the many bits of evidence together one can hardly avoid the conclusion that during the period of instrumental records, there has in fact been a fairly general if not over-all warming at least up to about 1940. There can be no doubt that the rise has not been uniform or symmetrical in respect to the poles, being least or nil in the middle latitudes of the southern hemisphere, and greatest in the high latitudes of the northern, especially in areas bordering the Atlantic ocean.

It is even more difficult to obtain a coherent picture of rainfall fluctuations on a regional basis than it is for temperature. Long term trends are lost in the normal short term variations and the consistently greater predominance of year to year variability over much smaller climatic fluctuations makes it imperative to test the reality of any alleged fluctuations. Lysgaard (1949) reported that the rainfall variation during the period 1910-40 showed positive anomalies for the Arctic and North temperate zone, in Mexico, in Southern India and South-west Asia, but negative anomalies

over the greater part of the United States, northern South America, Africa, Malaya, and Australia. While no comprehensive study of secular variations appears to be available for Canada, the studies of Thomas (1955) for the Atlantic coast and of Kendal and Thomas (1956) for the Prairie Provinces indicate that there was a trend towards smaller annual amounts in some areas. Dingle (1955), in a study of the change of precipitation patterns over the United States in the past sixty years did not find any trends in any part of the country and Landsberg (1960) agreed that there were no significant rainfall changes in the region. In a study of climatic fluctuations in Palestine since 1750, Neumann (1960) indicated a marked rise in rainfall from 1870 to a high level in 1890, then a rather sharp fall until about 1920, and finally a fall in 1920-50 of 10% below the 1846-1958 level. Rao, in a 1960 study for India concluded that there have been no statistically significant changes in either the annual or seasonal rainfall during the past eighty years. This confirms the findings of Pramanik and Jagannathan (1954).

By far the most interesting studies of rainfall fluctuations for tropical regions have been made by Kraus (1954, 1955a, 1955b, 1958). In his paper, "Secular Changes of Tropical Rainfall Régimes" (1955a), he indicated that tropical rainfall decreased abruptly at the end of the nineteenth century. He suggested a contraction of the rainy belt and a shortening of the wet season as the primary causes.

From the various studies referred to above, it does appear that something happened about the end of the last century to affect rainfall régimes in the tropics.

Studies by Ahlmann (1948), Leopold (1951) and Petterssen (1949) have indicated that there have been variations in temperature and secular changes in precipitation in the tropical areas of the Atlantic and the Caribbean Sea. They indicate too, that these variations are bound up with and closely related to variations in the general circulation over these regions. Indications are that in these areas, temperature fluctuations have not been spectacular and some estimates are that there has been a rise of between 0.5 and 0.7°C. Secular changes of rainfall however, seem to be of a magnitude sufficiently large to be of substantial consequence.

While it is generally recognized that changes in amount and spatial distribution of rainfall in the tropics are of importance, changes in régime, frequency and reliability could, in certain cases, be of critical import to agriculture and the water balance as a whole. If, as has been suggested, the rainy season has been shortened and/or has become less wet and complementarily, the dry season has become longer and more intense, the effects on the water balance and on agricultural pursuits could be of far reaching consequence. Soil moisture availability, and the provision of water for domestic and industrial purposes in a tropical area of increasing population are matters of practical concern. This writer is not unaware that factors

other than climatic fluctuations can produce similar effects on the water balance: for example, increased urbanization which changes infiltration rates, and deforestation and increased agricultural acreages which affect run-off rates. It is in recognition of the innumerable problems that can possibly arise from climatic fluctuations of the type and magnitude indicated by the various studies alluded to that this preliminary inquiry was undertaken into climatic fluctuations in Trinidad, an island in the Southern Caribbean. The study aims at (1) establishing the existence or non-existence of climatic fluctuations in Trinidad between 1921 and 1966, their spatial and temporal extent and their magnitude; (2) examining and analysing fluctuations in amount and periodicity of precipitation and the effects of these on the water balance equations and (3) assessing the extent to which these fluctuations may be reflected in or confirmed by tree-core samples taken in the island.

In climatic studies, the words "variation", "fluctuation" and "change" are used by different researchers in quite different senses. In what follows, "variation" refers to a short-term change in climatic elements for periods of a year or less; "fluctuation", on the other hand, connotes a sustained rise or fall in the mean value of climatic elements for periods of from five to fifteen years, while "change" means an upward or downward movement of the mean value of an element with a high degree of persistency over longer periods.

Past research in climatic change has demonstrated that deductions are largely dependent upon how the subject matter is treated. Climatologists are in agreement that a long-term study of temperature and/or precipitation should give an indication of the presence or absence of climatic changes in any given locality, but no standard method exists as to how these elements should be analyzed, or more importantly, what reality tests other than the usual statistical ones should be applied in order to prove their significance. It has been argued in climatological circles, that in the study of time series, particularly rainfall, it is desirable to have records for a long period of 80 to 100 years, otherwise results based on short-term records are likely to be misleading, and that actions on any fluctuations in short-term data should therefore be guarded. If validity of this argument is granted, then no work will be done for a long time in tropical regions since very few, if any network of stations in this part of the world yet has meteorological records for longer than the past 30-35 years. Court (1970) indicated that from a forecast and predictive point of view, when the median rather than the mean is used in the computations, a period of fifteen years gives better results than longer periods. Most of his research however, was centred on the United States, western Europe, Israel and Bermuda. Also, it has already been pointed out that records which may be deemed too short in mid-latitudes can give reasonably reliable results in the humid-tropics.

Again, for all regions there may be several periods within the record where rainfall has deviated considerably from the long-term mean and, although not being statistically significant on a long-term basis, it must have been quite significant to agriculture in the region. It is unfortunate that there are no established criteria as to what length of records should be used for testing the statistical significance of a fluctuation in a climatic element. A fluctuation that seems highly important, from a practical point of view, may also be statistically so by using a short period of record, but may become insignificant by using a long period of record.

Methods of determining the existence and magnitude of climatic fluctuations and change are many and varied, ranging from the traditionally simple analysis of departure from "normal", or the use of running-means, to the modern and more advanced variance-spectrum analysis of a time series. Each of these possesses advantages and limitations. "Moving averages" is a popular traditional method and though it is relatively simple and straight-forward it gives results which need to be accepted with caution, since no satisfactory statistical test of significance is available to assess as prominent, even those deviations which moving averages reveal as such. "Comparison of means of different periods" is a well recognized method and here the statistical "t"-test of significance can be employed.

Kraus has investigated fluctuations by means of residual mass curves. The quantity plotted graphically is:

$$Y_n = 100\sum_{\ell=1}^{n} \left(\frac{r_\ell}{\bar{r}} - 1\right) - C \qquad (1)$$

The constant, $C = 100\sum_{1}^{n}\left(\frac{r_\ell}{\bar{r}} - 1\right)$. In this method, Kraus does not apply any statistical test of significance for the fluctuations and his conclusions depend mainly on what may be seen from the Y_n graph. Barnard (1956) in a paper "Some Comments on Mr. Reynold's Notes," pointed out that while cumulative residuals are undoubtedly valuable, they need to be used with proper caution. He further stated that "it may be true that changes in a time series are often apparent on such a graph, but it is equally true that many such immediately apparent changes will turn out not to be real ones."

This writer recognizes the validity of most of the criticisms levelled against the various methods but feels that some of the apparent limitations can be overcome if the results or conclusions are qualified by clear statements of the assumptions made. Wherever it is possible, methods that lend themselves to statistical tests are used in this study. For example, comparison of means of different periods and the statistical t-test of significance are employed to test whether the mean of a sub period is significantly different from the mean of a long period. Thus if $\bar{x}_k$ is the mean of the first k years, then:

$$x_k = \frac{1}{k}\sum_{1}^{k} x_r \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

and

$$\bar{x} = \frac{1}{n}\sum_{1}^{n} x_r \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where $\bar{x}$ is the mean for the entire period of n years. Then it is shown that:

$$t = \tau_k\{k(n-2)/n-k-k\tau_k^2\}^{1/2} \quad \ldots\ldots\ldots\ldots \quad (4)$$

where $\tau_k = \dfrac{\bar{x}_k - \bar{x}}{s}$ is distributed as Student's t with n-2 degrees of freedom and s is the standard deviation of the entire series. The normality of the series is not only assumed but has been tested. In addition, sub-periods are compared with one another using the expression:

$$t = \frac{\left|\bar{x}_1 - \bar{x}_2\right|}{\sqrt{\dfrac{\hat{\sigma}_1^2}{n_2} + \dfrac{\hat{\sigma}_2^2}{n_2}}}$$

with $(n_1 + n_2 - 2)$ degrees of freedom, $\bar{x}_1$ and $\bar{x}_2$ are the means of the respective sub-periods and n_1 and n_2 the number of years in each sub-period respectively. Variance-spectrum analyses of the precipitation data for Trinidad were performed in an effort to discover oscillations that may be present in the series.

The data used in this study consist largely of time averages and totals chiefly for units of one month. This is a choice of necessity, determined by the need to simplify and to extract the utmost use from the data available. It must be emphasized however, that mean values of variable quantities are used as representations of the changing phenomena of

nature. It is presumptuous to claim that certain traditionally defined means have physical reality; that they faithfully depict the real world rather than provide an abstract picture useful in certain contexts. Average values are taken over particular space-time dimensions and have meaning only for these dimensions.

In Trinidad in 1966 there were about 154 rainfall observing stations. Four of these also collected other meteorological data. Figure I shows the location of these stations. The large circled numbers are hydrometric area designations. Of those stations that collected rainfall data, twenty-two had records for more than fifty years; thirty had records between thirty and forty years long, while fifty had records ranging from ten to fifteen years. The records of rainfall are in fact extremely variable in length ranging from fifty-eight to three years. In order to limit the size of this investigation to reasonable proportions, and to obtain results of the most general significance, ten of these stations were selected for use in the ensuing analyses. Their selection was based on length and continuity of record, and on the homogeneity of the data. Relevant information about each station is given in "index to station"--Appendix. Typical of the tropical regions is the fact that first order stations are few. Such stations tend to have come into existence at the beginning of World War II and to be located at airports where a knowledge of terminal conditions for aircraft

Figure 1

Location of Rainfall Recording Stations; Trinidad

(Taken from Trinidad Water Resource Survey, Interim Report #2)
M. M. Dillon Ltd.

is the primary concern. Other stations of long duration of observation tended to be associated with research institutions as is the case with St. Augustine and St. Clair, or with cocoa and sugar cane plantations which tend to concentrate on the measurement of rainfall. Thus there are only two first order stations in Trinidad: St. Clair and Piarco airport. The latter became operative in 1946. However, the stations selected for this analysis all have continuous, homogeneous records from 1921 to 1966 inclusive and are thought to be representative of the rainfall régimes of the island as a whole.

The basic elements analysed are temperature, precipitation and pressure. Monthly mean daily maximum and minimum temperatures, monthly mean temperature, monthly mean precipitation, and monthly mean daily pressure are utilized. The data for Trinidad as a whole were taken from the U.S. Department of Commerce publication "Climatological Data, West Indies and Caribbean, Annual Summary". The other data were abstracted from the records of the stations themselves in Trinidad.

In this study, Chapter II describes the research area and its climate in general and attempts an analysis of the pressure fluctuations. Chapter III deals with the analysis of the temperature series, while Chapter IV concentrates on analysing precipitation using different statistical methods. Chapter V attempts to isolate prominent oscillations in the precipitation time series through variance spectrum

analysis. The consequences of the findings described in Chapters II to V are discussed in Chapter VI with reference to the water balance, and dendrochronologic evidence is adduced to compare these findings. In Chapter VII the conclusions arrived at are enumerated and suggestions for further research are made.

CHAPTER II

THE STUDY AREA

The island of Trinidad, the most southerly of the West Indian islands lies off the north-east coast of South America between 10°3' and 10°44' north latitude, and between 60°55' and 61°56' west longitude. Rectangularly shaped, it covers an area of about 1,863 square miles. The island falls into six fairly obvious topographical regions shown in Figure 2--the Northern, Central and Southern ranges and the Caroni, Naparima and Nariva plains. The northern section of the island, the Northern Range, comprises an east-west range of densely forested mountains eight to ten miles wide and varying in height from 1500 feet to 3000 feet. Along the southern coast there is a range of hills considerably lower than the Northern Range. The highest point is 997 feet above mean sea level and it merges for much of its length into a surrounding peneplain. A chain of hills, the Central Range, runs diagonally across the centre of the island from north-north-east to south-south-west. It has a high point of 1009 feet. The lowland areas consist collectively of dissected alluvial terraces, dissected peneplains and several large areas of almost perenially inundated swampland.

The monthly mean temperature of Trinidad shows a relatively consistent distribution. The annual range of

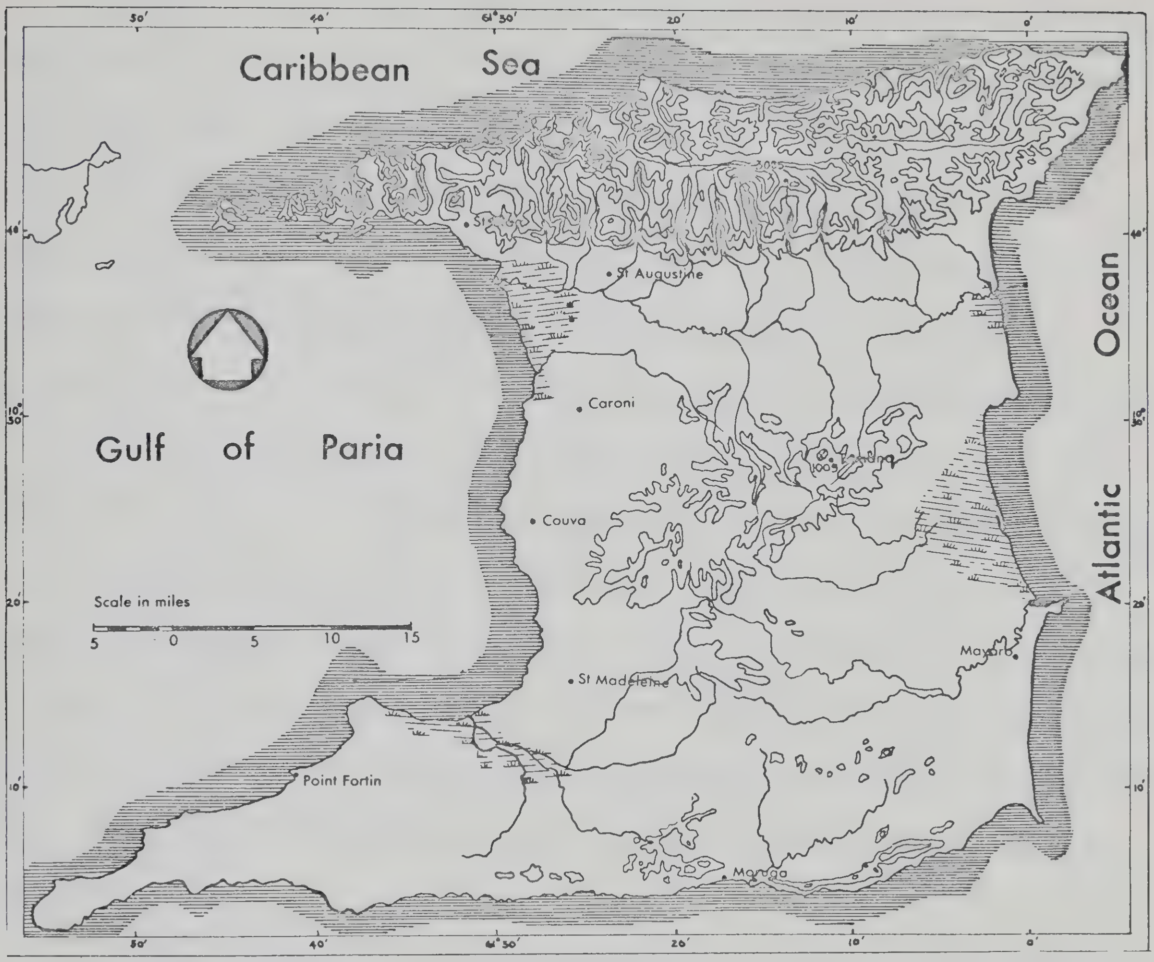


Figure 2

Map of Trinidad, West Indies, showing physical features.

temperature is about 3.5°F. The diurnal range however is quite large. The mean diurnal range over the period 1921-66 was 18.8°F. The mean daily maximum temperature is 89.6°F. while the mean daily minimum is 70.8°F. The island may be said to experience its four seasons every day since the diurnal march of temperature is analogous to the march of seasonal temperature in mid-latitudes. This is characteristic of most areas in the tropics.

The sun is vertically overhead twice annually and so the region experiences two temperature maxima, one in May (81.8°F.) and the other in October (81.0°F.). February is the coolest month with a mean temperature of 78.3°F. This temperature figure however is only 0.1°F. lower than the mean temperature for January. The hottest months are May and October with May being the hotter by 0.8°F. The period of overhead sun is not the hottest period. There is a lag of about one and a half months between the time of overhead sun, and maximum annual temperature. In addition, the period of greatest warmth is the wet season when presumably cloud build-up is at its maximum and the "green house" effect is accentuated. Further, the increased day length during that time of year makes for slightly longer periods of insolation and heating.

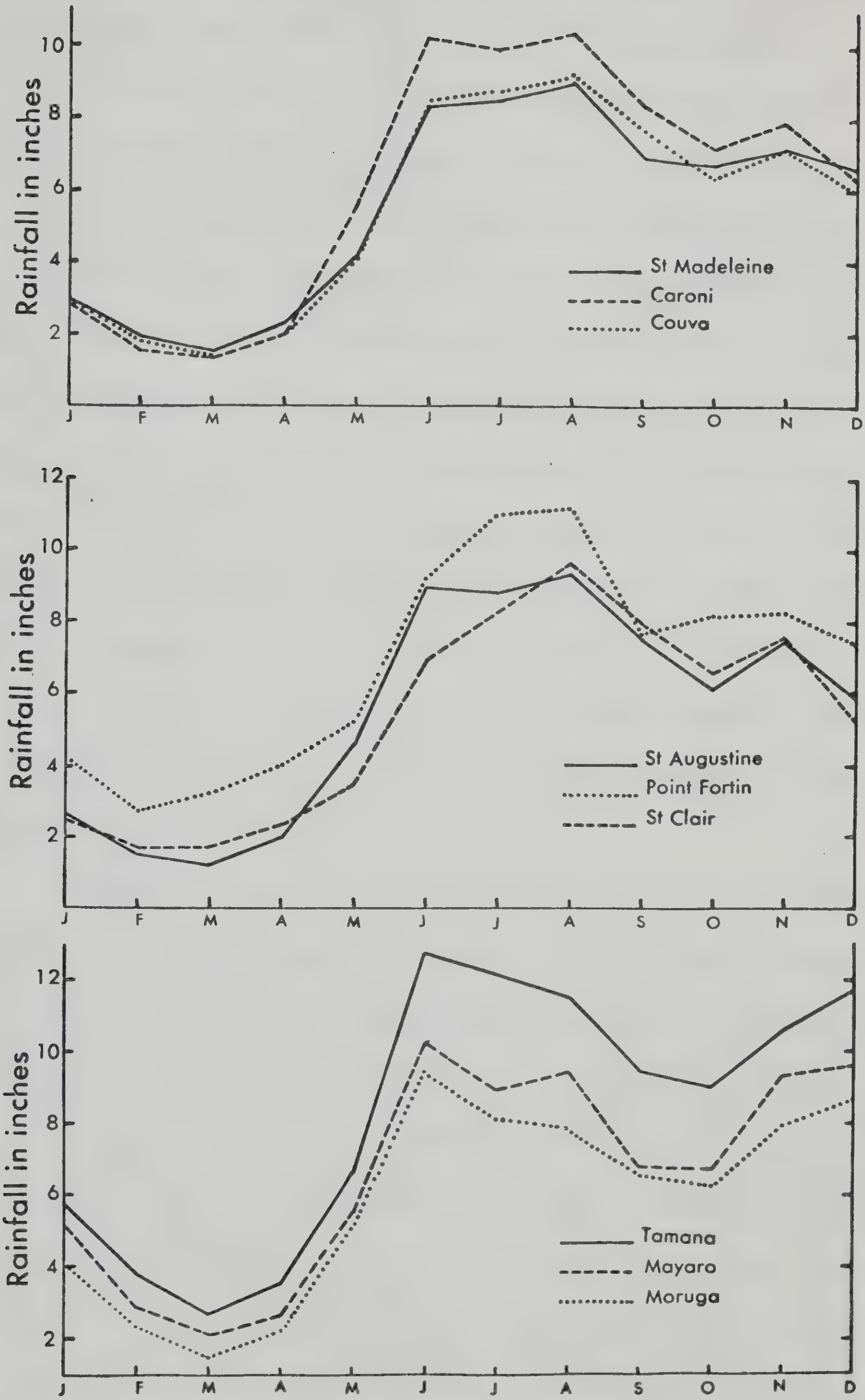
The climatic year in Trinidad is divided into two seasons, a dry season lasting roughly from January to May, and a wet season lasting roughly from June to December. The dry season is a period of comparatively strong trade winds blowing from the east-north-east and attaining an average speed of about seven knots during the day. The wet season is a period of heavier rainfall and weaker winds blowing from the east or east-south-east. It is also during the wet season that hurricanes occur. The dry season is not entirely dry but is a season of lower average monthly rainfall than the wet season. The beginnings and endings of these seasons

are liable to vary somewhat from year to year. Figure 3(a) shows the distribution of mean annual rainfall in Trinidad while Figure 3(b) shows the mean monthly distribution for the period 1921-1966 for nine selected stations in the island. (See Figure 2.)

The causes of the rainfall in the dry seasons are open to dispute. Riehl (1945), and Powis and Thompson (1945) consider that the rainfall of the Lesser Antilles in the dry season is due to outbursts of polar air from the North American continent moving south east across the Caribbean Sea giving rise generally to lines of instability showers but occasionally to prolonged spells of disturbed weather. Marsden and Fairley (1946) who investigated the weather of the area during the dry season, January to April 1946, concluded that the rainfall was not due to any cold outbursts but occurred in definite belts of two types which moved into the Caribbean Sea from the Atlantic. They suggest that these might be the remains of old cold fronts which had moved along the eastern side of the Azores high. They further noted that the cloud formations and sequences of the type which gave the worst weather were similar to those of warm fronts of temperate latitudes. On the other hand, it is generally agreed that the rainfall during the wet season in which most of the annual rainfall occurs is due to waves in the deep easterlies and to quasi-periodic oscillations in the inter-tropical convergence zone which is then south of the latitude of Trinidad.


Mean Annual Rainfall of Trinidad
Caribbean Sea
Atlantic Ocean
Gulf of Paria
Port of Spain
San Fernando
Legend
Above 130 inches
120–130 inches
110–120 inches
100–110 inches
90–100 inches
80–90 inches
70–80 inches
60–70 inches
50–60 inches
Scale in miles
1 0 1 5 10

Figure 3(a)



Mean monthly rainfall for 9 stations in Trinidad, 1921-1966

Figure 3(b)

During each of these seasons there is the additional effect of topography as a precipitation inducing factor.

In his study of rainfall distribution of Trinidad, Garstang (1959) indicated that discontinuities in the horizontal plane which may arise from differences in air masses may be discounted, and that vertical transportation of air either in the form of convection, orographic lifting or widespread convergence or all three factors in a single complex pattern are of over-riding importance in the rainfall distribution pattern in the island. During the dry season the rainfall distribution follows the relief of the island fairly closely, suggesting that during a period when disturbances of a synoptic scale are few, local features govern the distribution of precipitation. During the wet season relief no longer dominates the pattern.

There are three distinct periods in the region which co-incide with the seasonal variation of the wind and moisture field in the lower troposphere--June through October with a consistently high moisture level; January to April with low humidity values and an intermediate period in which the moisture levels climb or descend. Monthly averages of hourly relative humidity and monthly averages of hourly wind speeds in knots for the period 1946-66 inclusive were abstracted from the record of observations at Piarco. Plots of the mean of the two elements for the twenty-one year period are shown in Figure 4. There is an inverse relationship between the

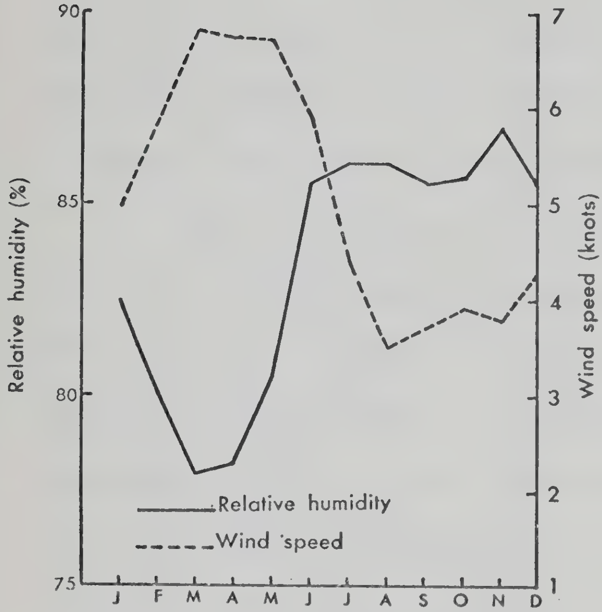


Figure 4 Monthly mean hourly relative humidity and wind speed at Piarco Trinidad, 1946-66

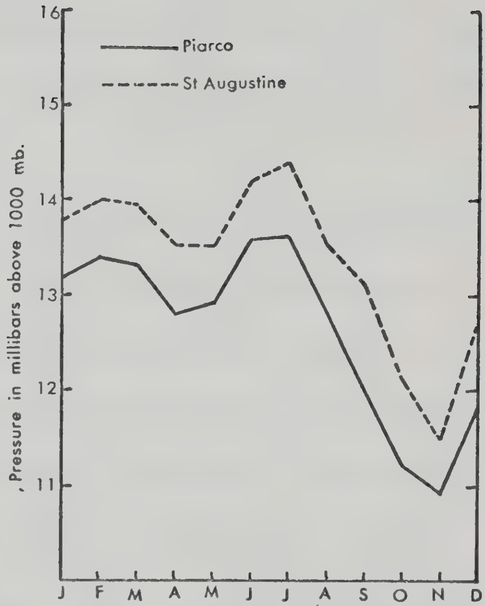


Figure 5 Mean monthly sea level pressure at St Augustine and Piarco, Trinidad

mean relative humidity and the mean wind speed. In the period January to May when the relative humidity is lowest, the wind attains its highest speeds. The converse is true in the period June to December.

Mean monthly sea level pressure at Piarco computed from observations made at eight synoptic hours, and mean monthly sea level pressure at St. Augustine computed from two daily recordings--0800 local time (1200 G.M.T.) and 1600 local time (2000 G.M.T.) respectively are averaged over a period of twenty-one years for Piarco, and thirty-six years for St. Augustine. These give curves (Figure 5) with two maxima and two minima during the year. The two minima occur in April and November--the November minimum being the deeper. The larger of the two maxima occurs in July. The amplitude

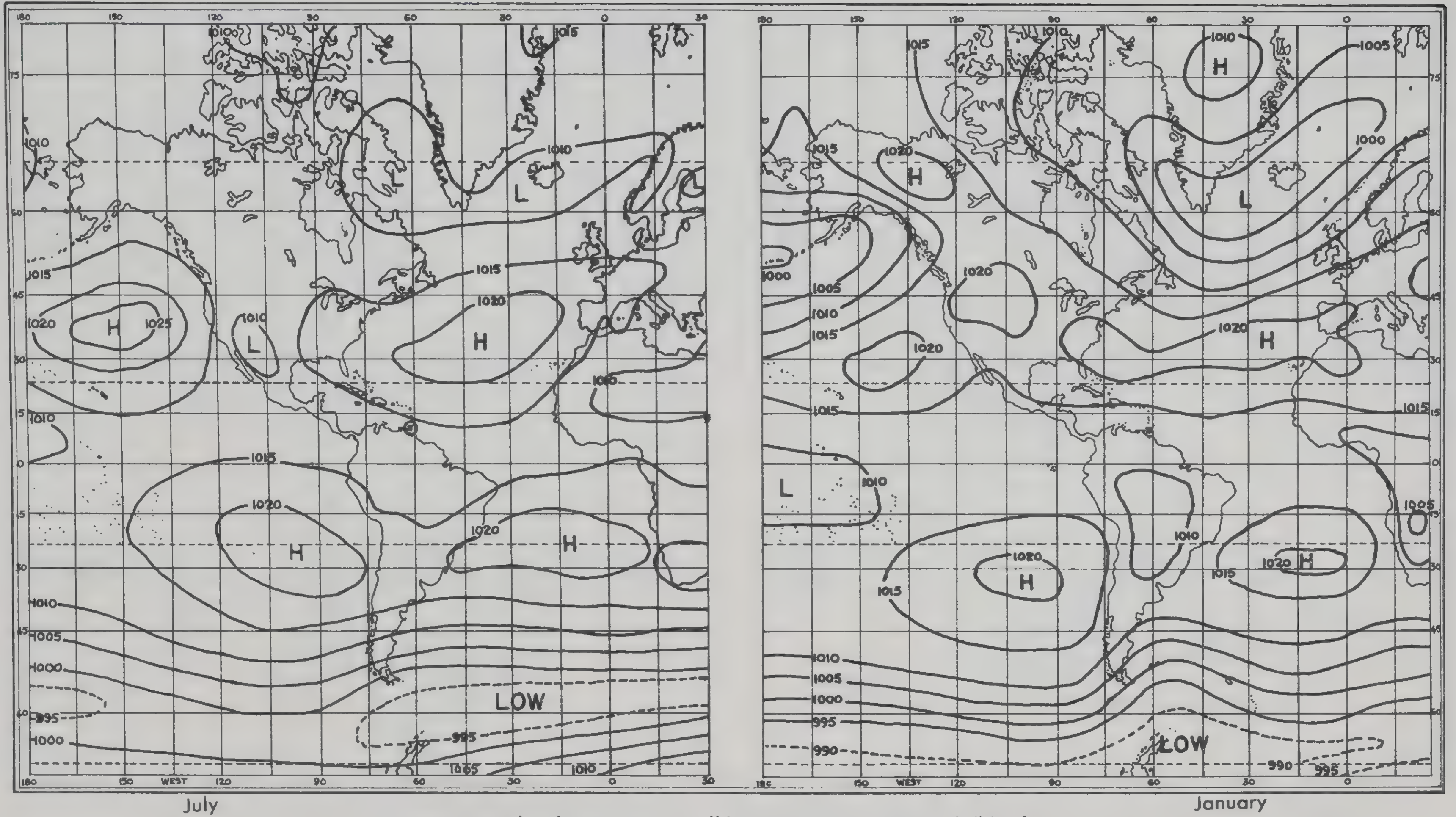
of the curve is between three and four millibars. The characteristic shape of the curves is representative of the broad seasonal changes in sea level pressure which take place over a large area surrounding Trinidad.

The doldrum belt of low pressure lies fairly stationary over the Atlantic to the east of the Amazon throughout the year. It extends westwards over the Pacific from the Panama neighbourhood. The lack of symmetry in the Trinidad pressure curves arises from the peculiar shape of the Americas, and must be explained in terms of the movement of the Azores anticyclone, the thermal depression which forms over Central Brazil in January to March and the similar depression which forms over California in September and October.

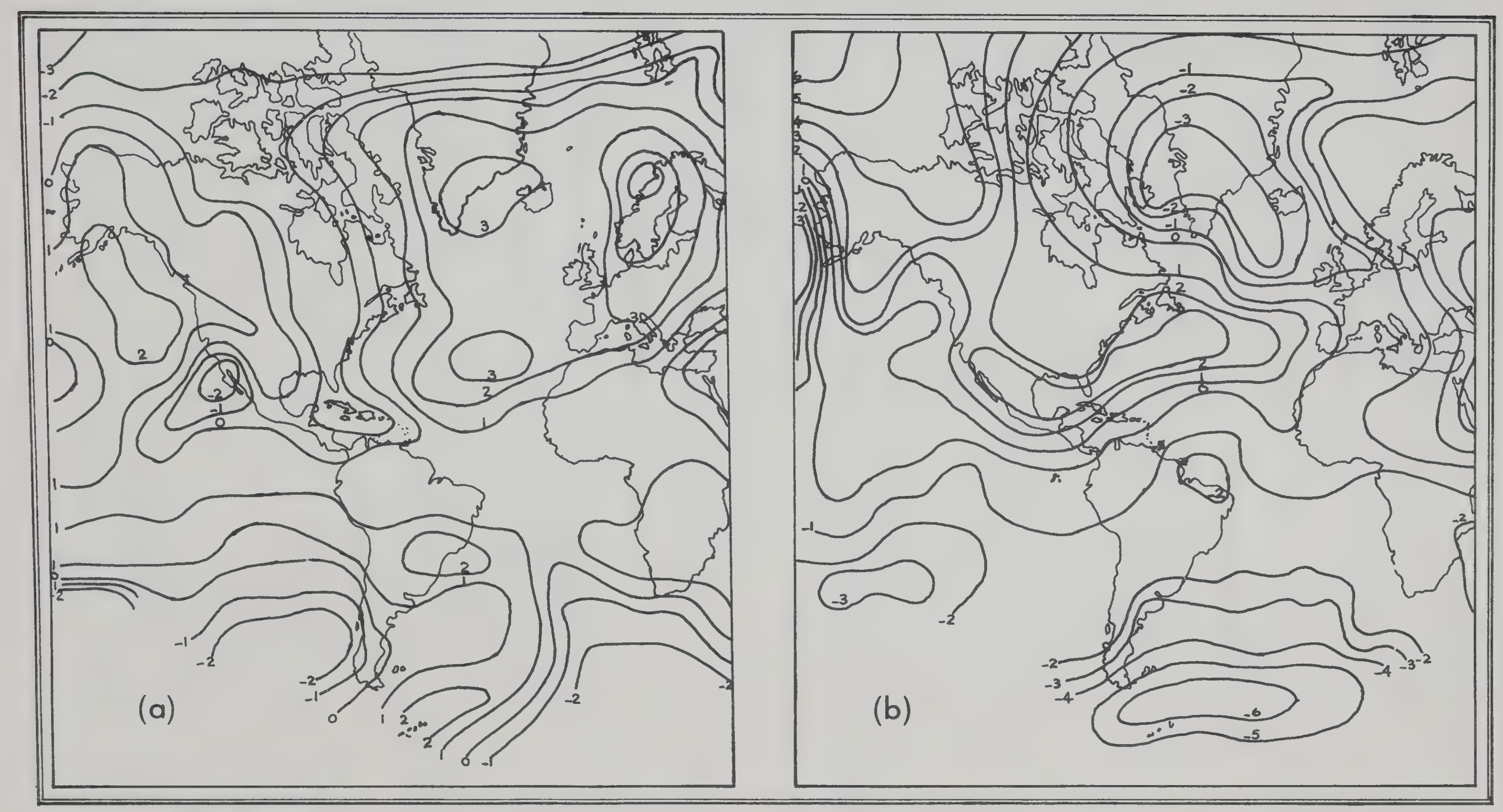
In December, January and February when the sun is in the southermost part of its course, the thermal low over Central America is most strongly developed, the line of lowest pressure over South America is therefore displaced to the south and Trinidad comes under the influence of the outer edge of the Azores anticyclone which at this time of minimum intensity is however, extended to its fullest in the southwesterly direction. In April, the sun is overhead in the southern Caribbean on its northward course, the thermal low over Central Brazil has disappeared but the new thermal low over California is beginning to form. The Azores anticyclone retracts somewhat and the resultant line of lowest pressure pivoting on the mouth of the Amazon moves nearer to Trinidad

and causes the first minimum on the mean pressure curve. In June and July the California low has become well developed but the Azores anticyclone has also intensified, extended its periphery over the Lesser Antilles, and has driven the line of minimum pressure over the Central American Isthmus. This causes the second maximum in Trinidad. A second minimum of pressure is associated with the sun's southward journey. It is deeper than the first because the surface temperature of the whole Caribbean area has been raised, the seasonal variation being 4° to 5°F. These relationships are shown in Figures 6 and 7. Figure 7 shows the distribution of the change in mean pressure by means of isallobars. The periods chosen for illustration represent the highest rate of change.

It has just been shown that there are variations in mean sea-level pressure during the year in response to the sun's migration; to the characteristic distribution of land and ocean surfaces, and to the thermal character of land and sea. Also shown is the fact that the annual precipitation in Trinidad seems to occur in distinct patterns. These patterns can be quantitatively classified. The problem arises whether it is practical to determine whether circulation patterns are uniquely associated with those of precipitation. Extensive investigation by Solat (1948) and Namias (1947) confirm the view that the mean pressure anomaly chart is a satisfactory tool for this purpose. It would be most desirable to extend such analysis to upper air charts. However, since sufficient



Mean sea level pressure in millibars for:(a) January and (b) July
(adapted from Haurwitz and Austin [1944])
Figure 6



Seasonal changes of mean pressure distribution in millibars for :(a) April-May and (b) October-November
(Modified from Namias, [1943].)

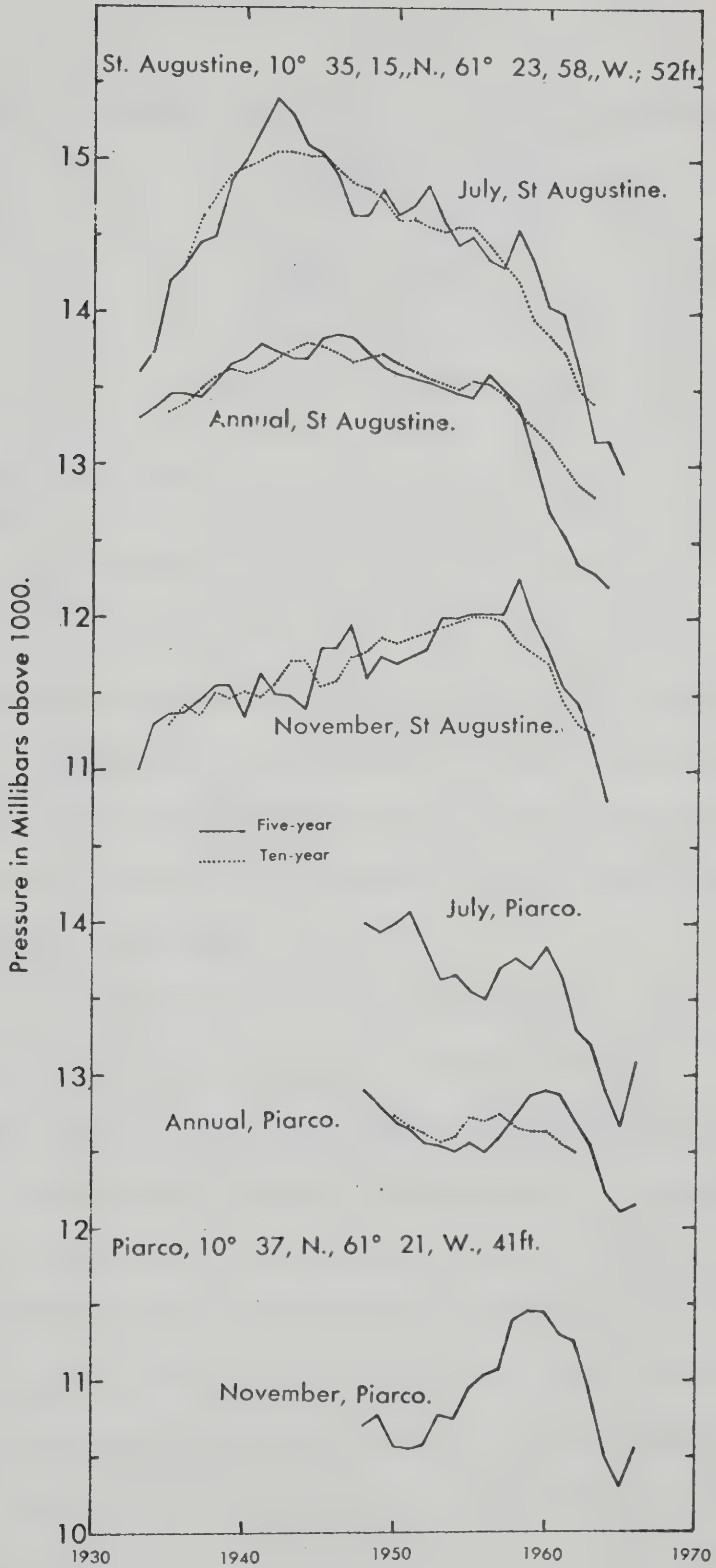
Figure 7

upper air data are unavailable for the time period under consideration here, resort must be made to sea-level data.

Five and ten-year cumulative means of mean daily pressure at St. Augustine and Piarco in Trinidad were calculated for the period for which sea-level pressure data are available. The calculations were based on the means for July, for November and for each year. The results are plotted in Figure 8. The July curve for St. Augustine shows a rise in mean sea-level pressure between 1933 and 1942, and a fluctuating but declining trend from 1943-66. The decline has been very rapid after 1957. The November curve indicates that the mean sea-level pressure of that month increased slightly up to 1946, and decreased after this period. The greatest decrease occurred after 1957.

The curves for Piarco show identical fluctuations. The general indication is that at both stations there has been a consistent decrease in mean sea-level pressure for July since 1942, and an increase in mean sea-level pressure for November up to and including 1957. After this time there was a reversal. It is well to note that in all the curves the decreases after 1957 are most marked.

The seasonal mean sea level pressure fluctuations for St. Augustine and Piarco were also investigated. The periods chosen were January to April, and June to November, representing the dry and wet seasons respectively. The statistics are given in Table I. The coefficient of variation which



Five and ten-year cumulative means of monthly mean daily pressure at St. Augustine and Piarco, Trinidad:

Figure 8

TABLE I

SEA-LEVEL PRESSURE STATISTICS FOR ST. AUGUSTINE AND PIARCO
(values in mb.)

	ST. AUGUSTINE			PIARCO		
	Dry Season	Wet Season	Annual	Dry Season	Wet Season	Annual
Mean	13.1	13.9	13.4	12.3	13.2	12.6
Median	13.2	14.1	13.5	12.5	13.1	12.6
Standard Deviation	0.6	0.6	0.6	0.4	0.5	0.4
Variance	0.4	0.5	0.4	0.3	0.4	0.3
Coeff. of Variation	4.3%	4.6%	4.2%	3.6%	3.7%	3.2%

gives some indication of the variability of distribution in time is rather small, although the wet season shows the largest values at both stations. This supports an earlier suggestion that the wet season is in fact a period of greater atmospheric activity.

In addition to the above method, cumulative percentual deviations from the mean of monthly mean daily sea-level pressure for the two stations were calculated both for the dry season and the wet season. The graph of values obtained is given in Figure 9. The period 1933-57 was one of above average in terms of sea level pressure at St. Augustine. There was in fact a steep rise, but there was a steeper drop after 1957. At Piarco there were rises in the periods 1945-49 and 1951-61 and decreases in the periods 1950-55 and 1962-66. The fluctuations in sea level pressure at Piarco had an average period of eight to ten years or alternatively four

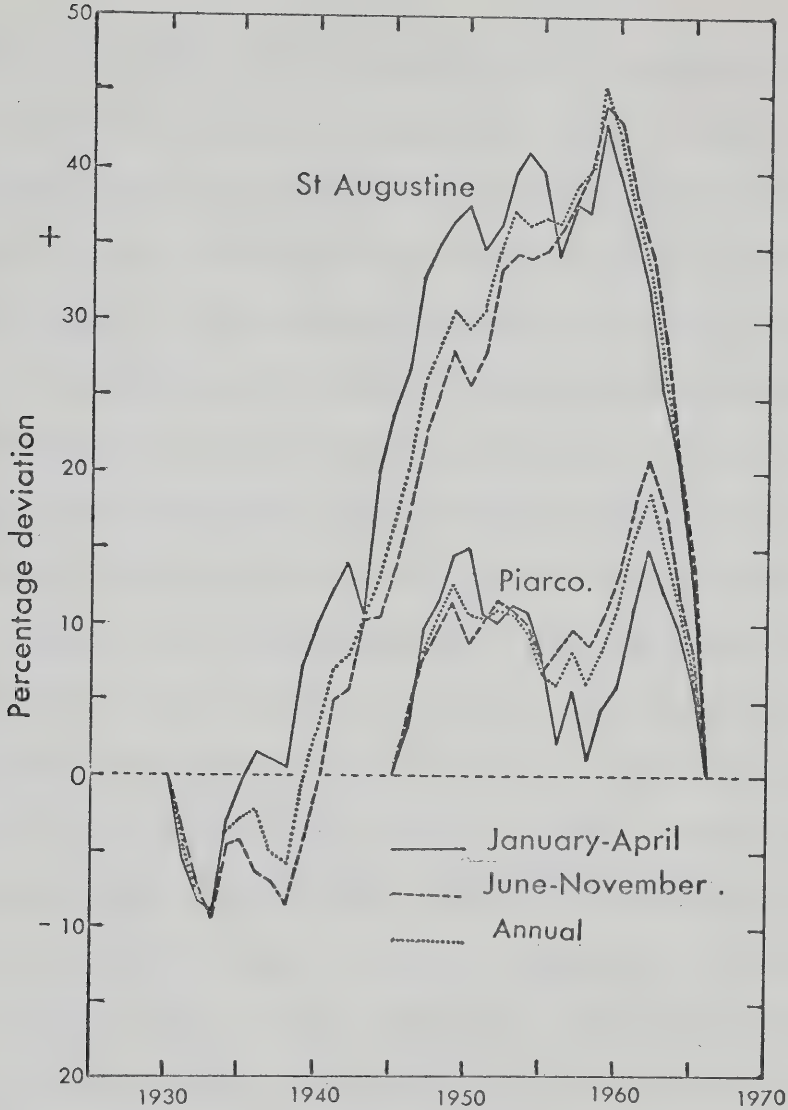


Figure 9 Cumulative percentual deviations from the mean of monthly mean daily sea level pressure for two stations in Trinidad .

to five years of rising pressure followed by similar periods of falling pressure. It will be shown later that this same oscillatory movement is evident in the precipitation data.

In the Caribbean region the most prolific single wet season rain producer are perhaps hurricanes, but their relatively infrequent appearance at any given locality within the

Eastern Caribbean south of about 18°N. latitude makes it unlikely that they greatly affect the long range averages. In the region north of 18°N. latitude and west of 75°W. longitude, and in the Eastern United States and Mexico the effect of hurricanes on the precipitation totals for particular months is probably more marked since these areas are affected more frequently during consecutive years. During recent years there has been frequent speculation on the probability that the annual number of hurricanes is on the increase. Dunn and Miller (1964) have indicated that over the past seventy years an average of eight hurricanes per year has occurred. This average has increased to nine per year over the past forty years and to ten per year during the past twenty years. They have also shown that in 1956 and 1957 the number of hurricanes fell off to eight. This overall increase is probably due in part to better detection techniques, but their figures seem to show a significant increase in the number of hurricanes beginning around 1930. The gradual warming of the atmosphere began, as will be shown later, about that time and the greater number of hurricanes may be related to that warming trend. During the past several years, the warming trend has been reversed and the reversal corresponds well with the time of lower frequency of hurricanes. The hurricane season in the Caribbean region spans the period June to November, and this period is coincident with the rainy season in Trinidad.

Attention will be drawn repeatedly to the fact that

the total precipitation for individual years has fluctuated markedly from the longer-term means; for example 1951. One may therefore question how dependent the wet season totals for individual years are on the occurrence of hurricanes, or whether there is some correlation between the wettest months of the wet season and the frequency of hurricanes. The majority of Caribbean hurricanes occur in the western and northern Caribbean Sea, (Figures 10, 11, 12, 13, 14) and even those that originate in the Eastern Caribbean travel on a westerly trajectory that is usually north of Trinidad.

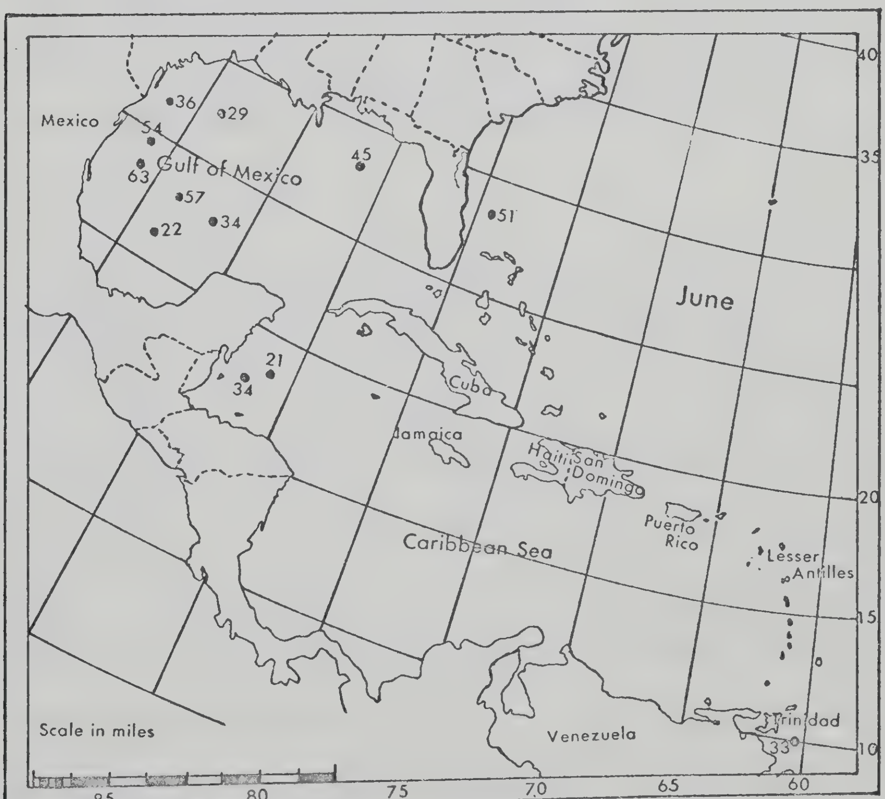


Figure 10 Locations where Tropical Cyclones reached hurricane intensity, June, 1921-66. The two digits at each location indicate the year.

(Adapted from U.S. Weather Bureau Climatological Data National Summaries, Vols. 1-14)

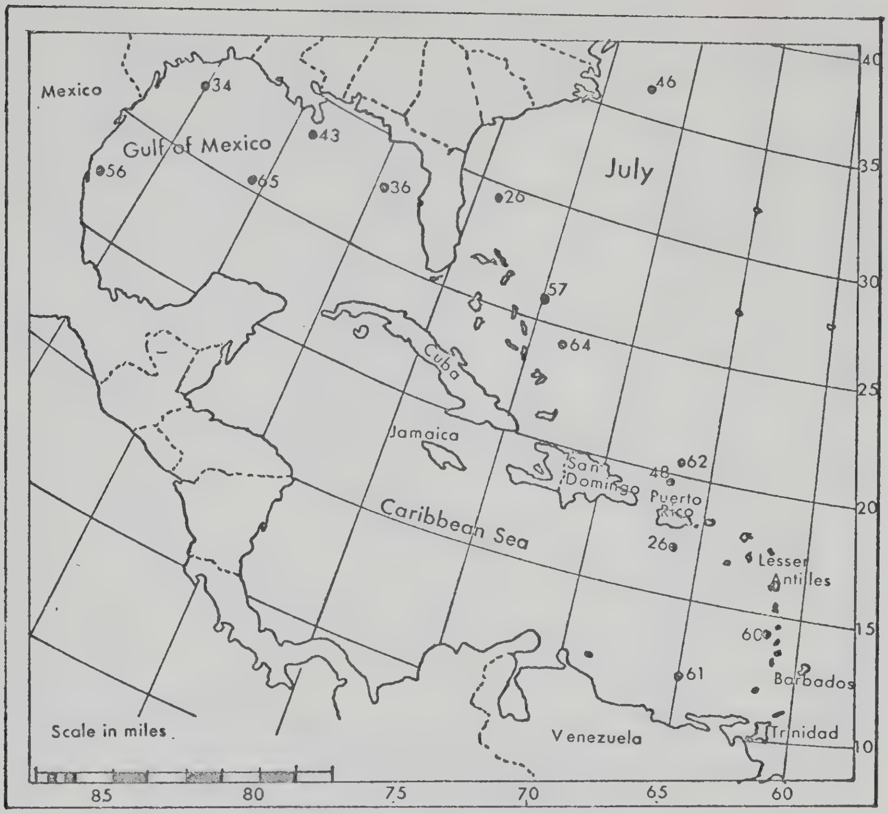
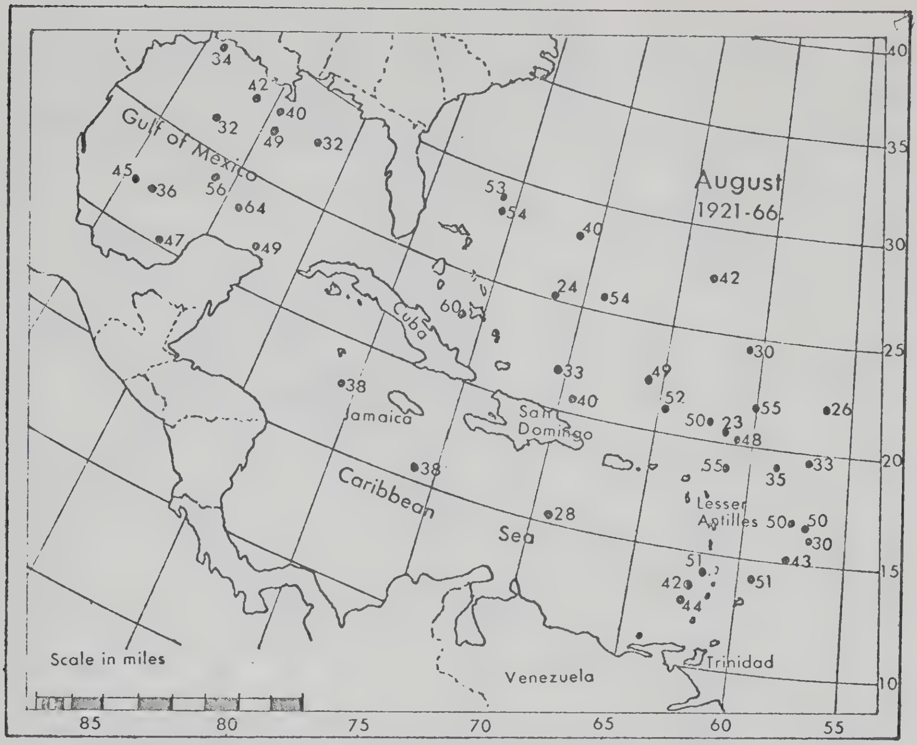


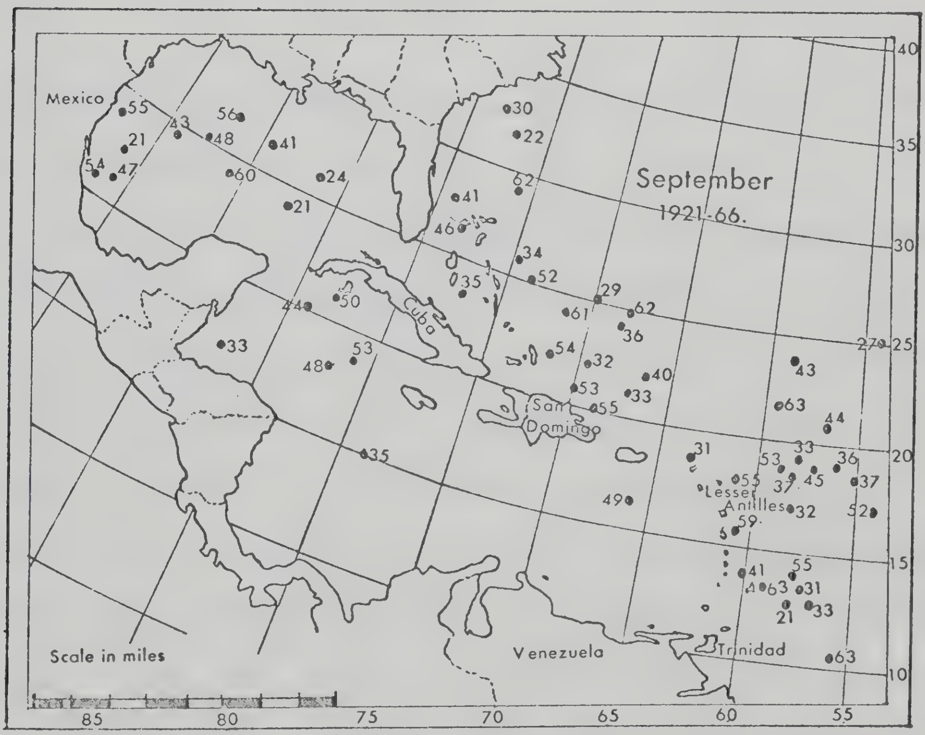
Figure 11 Locations where Tropical Cyclones reached hurricane intensity, July 1921-66. The two digits at each location indicate the year
(Adapted from U.S. Weather Bureau Climatological Data National Summaries, Vols. 1-14)

This is not to say that Tropical Cyclones do not originate in the Eastern Caribbean and, that these tropical cyclones do not perhaps affect precipitation distribution in Trinidad during the rainy season; nor is it meant to deny that some of these tropical cyclones may not, and do not develop into hurricanes in the eastern and northern Caribbean region. But "tropical cyclones" are not synonymous with "hurricanes", and the former is only classified as a hurricane when the wind velocity within the system exceeds 73 m.p.h., 30 feet above ground. The Eastern and Southern Caribbean areas are therefore least affected by hurricanes. The Hurricane of June



Locations where Tropical Cyclones reached hurricane intensity, August
The two digits at each location indicate the year .

Figure 12



Locations where Tropical Cyclones reached hurricane intensity, September
The two digits at each location indicate the year .
(Adapted from U.S. Weather Bureau Climatological Data National Summaries, Vols. 1-14)

Figure 13

Figure 14 Locations where Tropical Cyclones reached hurricane intensity, October
The two digits at each location indicate the year
(Adapted from U.S. Weather Bureau Climatological Data National Summaries, Vols. 1-14)

1933 is the only one in the entire hurricane record whose centre passed over Trinidad. The total rainfall for that June was 11.8". This is by no means the highest on the record for the period under consideration. June 1944 (17.3"), November 1928 (14.9"), August 1949 (14.9°), June 1958 (14.2") and February 1951 (13.9") are examples of higher monthly totals. In none of these months however, were hurricanes near enough to the island to have influenced the monthly totals, the majority of which occurred within the hurricane season. Certainly there was no occurrence of hurricanes in February, 1951.

It must be acknowledged though, that it is quite unlikely that the exact rainfall in any hurricane is ever

known, since after the wind reaches 50 m.p.h. or more, it is possible that not more than 50% of the rainfall is actually caught in the rain gauge (Tannehill, 1956). In addition, where rainfall exceeds ten inches in such short periods overflow of most rain gauges takes place. On July 26th, 1933, a hurricane appeared south-east of Antigua and travelled on a westward path. This storm could have been responsible for the 12.5 inches in July 1933, the largest monthly total for that year. The only other periods during which hurricanes passed within effective distance of Trinidad were the seasons of 1928 and 1938. On August 3rd, 1928 a storm passed near Trinidad. It was not of great energy. Another passed near the island on August 7th of that year following the same course. It had no great force (Tannehill, 1956). The highest monthly precipitation for that year occurred in November (14.9"). The storm of August, 1938,was first observed not far from the north west of Trinidad. In addition there were three storms in October and one in November of that year, all of minor character (Tannehill, 1956). The largest monthly totals for 1938 occurred in August and November--12.3 inches and 12.8 inches respectively.

Table 2 attempts to show the correspondence between the wettest months and the occurrences of hurricanes. The ten wettest rainy seasons of the period were chosen. The rainy seasons referred to in the table are in descending order of wetness.

TABLE 2

THE RELATIONSHIP BETWEEN THE WETTEST MONTHS AND HURRICANE OCCURRENCE

YEAR	TOTAL WET SEASONAL RAINFALL	WETTEST MONTH AND RAINFALL VALUE (inches)	MONTH OF HURRICANE OCCURRENCE (RAINFALL inches)
1933	66.5"	July (12.5)	June (11.8)
			July (12.5)
1964	62.0"	June (13.5)	-
1966	61.5"	June (16.1)	-
1924	61.5"	July (13.3)	-
1955	61.4"	July (12.7)	Oct. (8.6)
1951	60.6"	June (15.5)	-
1944	58.5"	June (17.3)	-
1938	57.7	Nov. (12.8)	Aug. (12.3)
			Oct. (5.5)
			Nov. (12.8)
1941	57.7"	July (11.9)	-
1928	57.6"	Nov. (14.9)	Aug. (9.8)

The following years are years in which hurricanes did occur in the region. The format is the same as for Table 2. The indications are that there is very little correspondence

1956	52.3"	Aug. (12.5)	Aug. (12.5)
1958	55.5"	June (14.2)	June (14.2)
			Aug. (8.1)
			Sept. (4.1)
1959	45.7"	Oct. (9.1)	Aug. (8.3)
1961	54.2"	July (10.8)	July (10.8)
			Oct. (8.2)
1963	46.6"	June (9.8)	Sept. (9.7)

between the occurrences of wet years and the occurrences of hurricanes in or near Trinidad. The wettest year of the period, 1951 (107.1") was a year when hurricanes passed far north of Trinidad in the months of August and September, yet the highest monthly totals occurred in February (13.9"), June (15.5") and November (10.2"). Of the fifteen months during which there was hurricane activity in the Eastern Caribbean only on five occasions has the month of hurricane occurrence coincided with the month of the greatest precipitation and only in two cases was this true for the ten wettest years of the period under investigation.

Table 3 shows the relationship between the deviation from the mean of monthly rainfall during the hurricane season

TABLE 3

DEVIATION OF MONTHLY RAINFALL TOTALS FROM THE MEAN AND HURRICANE OCCURRENCE

	June	July	Aug.	Sept.	Oct.	Nov.
No. of times mean for the month was exceeded (1921-66)	21	21	23	23	22	22
No. of hurricane occurrences when monthly rainfall exceeded the mean. (1921-66)	1	2	5	4	1	1
No. of times hurricane occurred and rainfall for the month less than mean.	-	2	7	3	2	-

and the occurrence of hurricanes within a 5° square around Trinidad, while Figures 10 to 14 indicate the locations

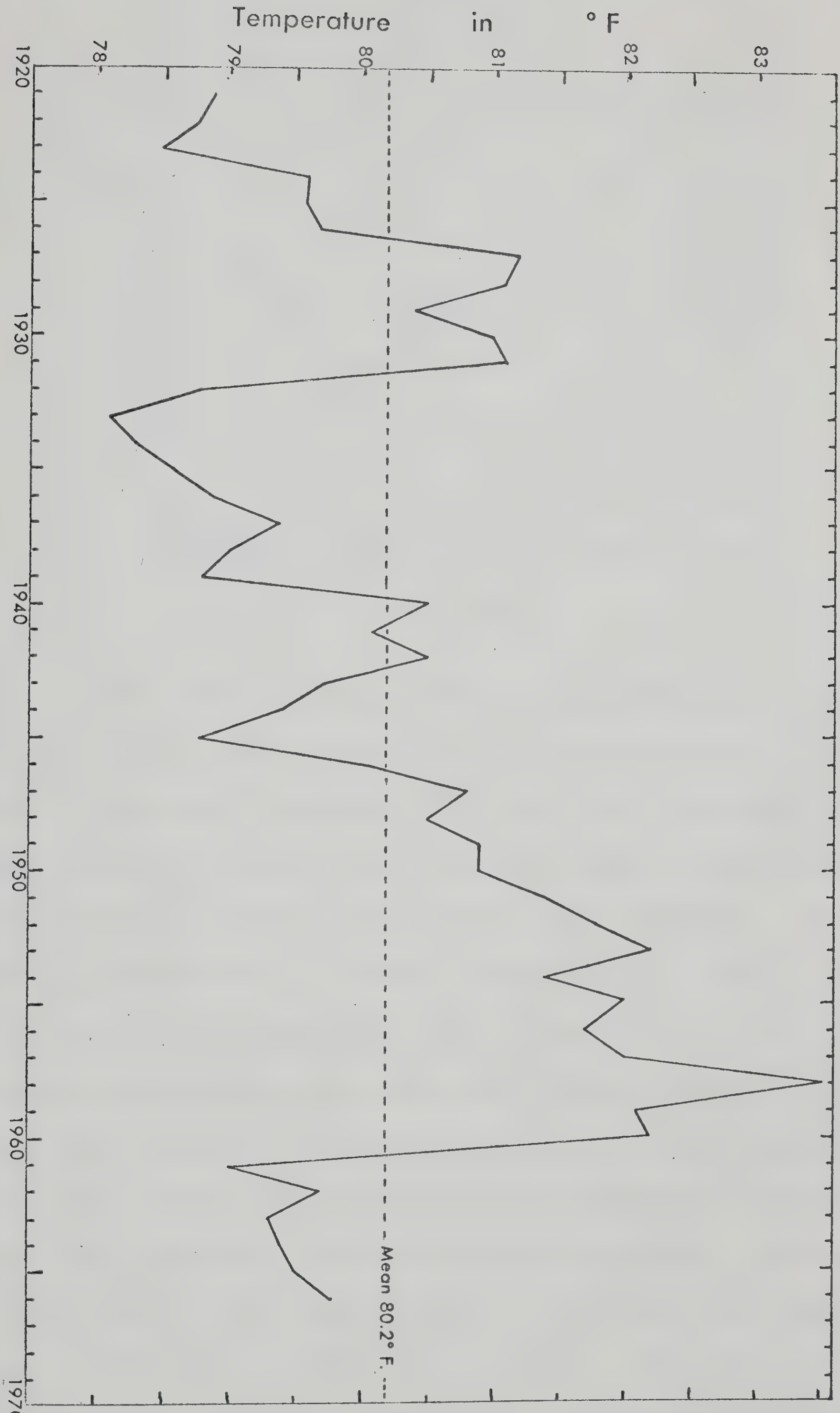
where tropical cyclones reached hurricane intensity. It is intended to show the frequency of occurrence of hurricanes within that 5° square in the period 1921-1966. The probability that a month in which the mean monthly rainfall was exceeded will be a month in which a hurricane occurred within the 5° square surrounding Trinidad was 5%, 10%, 22%, 5%, 4% for the months of June to November respectively. However, in August there were one and one-half times as many hurricanes occurring when the monthly total did not exceed the mean as when the mean was exceeded. In October this figure is twice, while in July and September as many hurricanes occurred when the mean was exceeded as not. It seems safe therefore to conclude that hurricanes, regardless of their being an integral part of the Trinidad summer climate, do not deform the rainfall distribution pattern in such a way that if true fluctuations do exist they may be hidden by hurricane occurrences.

The foregoing synthesis of Trinidad's climate makes only passing reference to cloud cover and humidity among the climatic elements, while relatively more detail was given on the influence of hurricanes on unusual precipitation totals. In the ensuing chapters temperature and precipitation will be further analysed for evidence of fluctuations. The importance of any existing fluctuations can be better appreciated if the long term average climatic conditions are fully grasped.

CHAPTER III

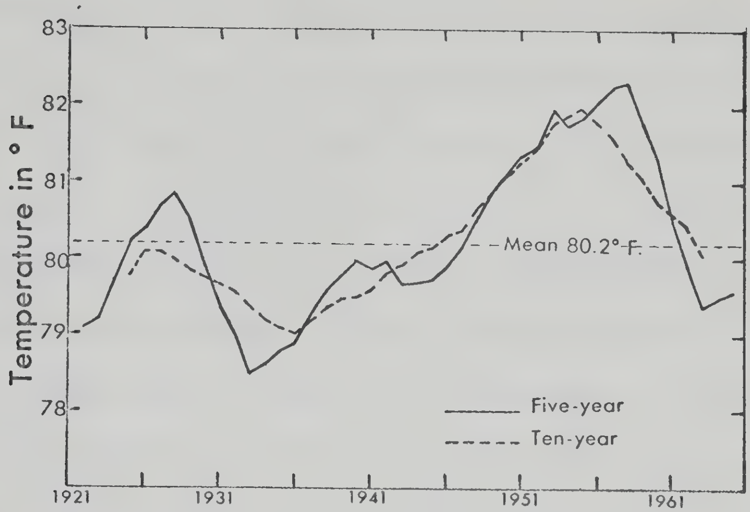
TIME-SERIES ANALYSIS OF TEMPERATURE

It is not expected that temperature fluctuations will be as noticeable in the tropical regions as they have been in mid-latitudes and polar regions. However, the studies which have verified temperature increases in the extratropical regions during the first forty years of this century also left it open to supposition that the mid-latitudes were not unique in this trend. In order to discover if any fluctuations are evident in Trinidad, monthly mean temperature for the island as a whole during the period 1921-1966 was investigated. The annual mean for the forty-six-year period was 80.2°F., with a temperature range between the mean of the coldest year and that of the hottest year of 5.3°F., the hottest year being 1958 with a mean annual temperature of 83.6°F. and the coldest year being 1935 with a mean annual temperature of 78.3°F. The graph of mean annual temperature (1921-66) is presented in Figure 15. The curve seems to indicate two, and possibly three régimes dominating the record. Five and ten-year cumulative means of annual temperatures were also calculated and graphed. The results are shown in Figure 16.



Mean Annual Temperatures, Trinidad (1921-66)

Figure 15



Cumulative means of mean annual temperature for Trinidad, West Indies. 1921-1966

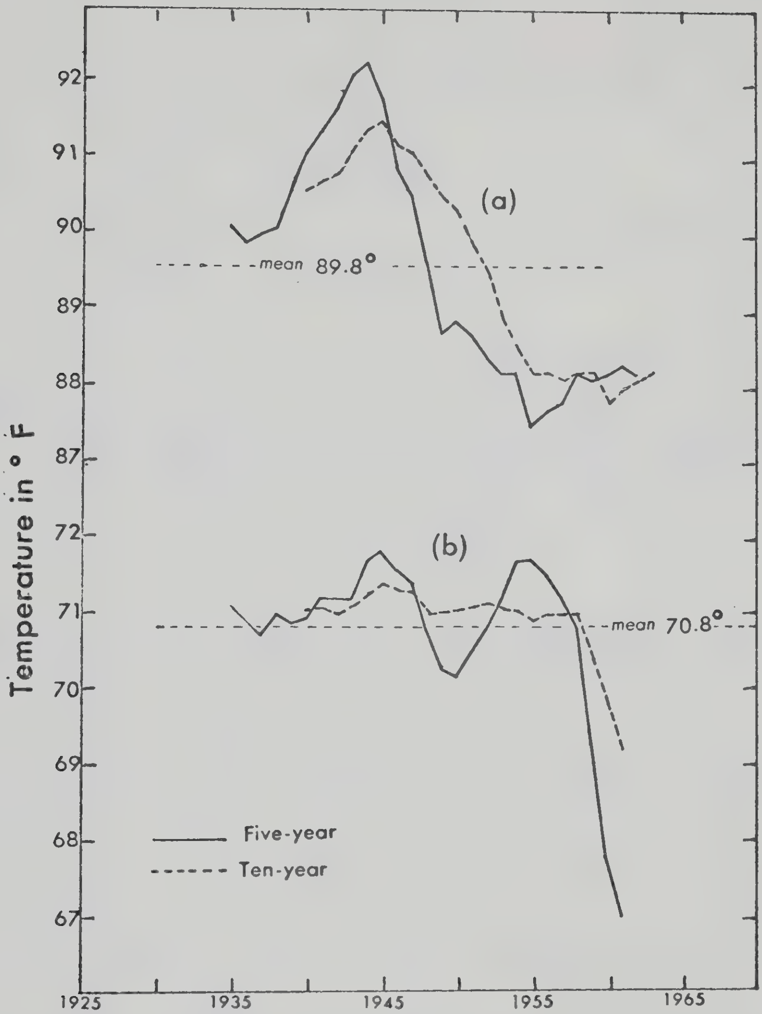
Figure 16

The impression is that in Trinidad there have been, in the period under investigation, fluctuations in temperature of irregular lengths. The curve of five-year cumulative means indicates that there have been at least three periods during which temperatures rose and fell, while as a whole, maintaining a general rising trend. The lengths of these periods are variable with an average of about fifteen years, and covering the years 1921-1932, 1933-1945, and 1946-1966. One dominant feature here is that during the first two periods the mean annual temperature fluctuated generally below the mean of the whole period, rising above it for most of the third period. The rise after 1945 to the peak in 1958 being 4.8°F. In general, the curves seem to indicate that a warming trend started around 1933 with an apparent reversal commencing around 1958. The magnitude of

this warming is about 4°F. In terms of tropical maritime temperature variations this is quantitatively significant and well above the margin of instrumental and observational error.

Further smoothing of the curve to ten-year cumulative means reduces the amplitude of the fluctuations but does by no means eliminate them. What it does, however, is give a clearer indication of those periods which are most prominent. Two of these stand out--a fluctuating but nonetheless warming trend during the first part of the period, and a cooling trend beginning at or about 1956-58 and continuing to the end of the period under review. These two trends fit the findings of Callendar (1960) who found "a small but significant rise in the tropics (0.17°C.) commencing 1915."

Investigation into the extent to which the fore-mentioned fluctuations were dependent upon fluctuations in either the monthly mean daily maximum temperature, or monthly mean daily minimum temperature or in both of these, was attempted. The records of two stations in the island were analyzed--that of St. Clair, lat. 10°41'N., long. 61°31'W., and situated 67 feet above sea level, and that of Piarco International Airport, lat. 10°37'No., long. 61°21'W., and lying 41 feet above sea level. As in the earlier analyses, five and ten-year cumulative means of the monthly mean daily maximum and monthly mean daily minimum temperatures were calculated. The resulting curves are shown in Figures 17 and 18. The records are of unequal lengths--that of St. Clair

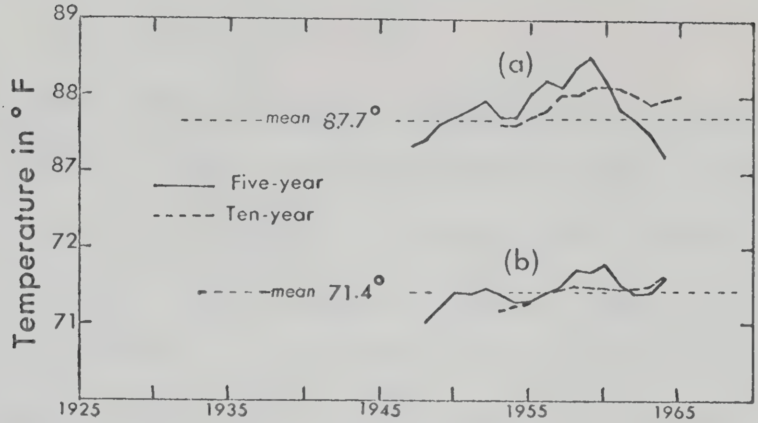


Cumulative Means of (a) Monthly Mean Daily Maximum Temperature, (b) Monthly Mean Daily Minimum Temperature at St. Clair, Trinidad (1931-66).

Figure 17

extending from 1931-66, and that of Piarco from 1946-66. The choice of stations was not fortuitous, but one of necessity since these were the only stations with continuous homogeneous temperature data worthy of analysis.

It is quite evident from the graphs in Figures 17 and 18 that fluctuations in the mean annual temperature of the island during the period under study were perhaps affected more by fluctuations in the mean daily maximum



Cumulative Means of (a) Monthly Mean Daily Maximum
(b) Monthly Mean Daily Minimum Temperature
at Piarco, Trinidad (1944-66).

Figure 18

temperature than by the mean daily minimum. At St. Clair, the curves of monthly mean daily maximum temperature show opposite trends to the curves of mean annual temperature for the island as a whole (Figure 17), except in the period 1933-42 when the directions were the same. The opposite trends are most pronounced after 1944. Between 1944 and 1956/58, the mean annual temperature of the island increased while the mean daily maximum at St. Clair decreased. The reverse is true in the period 1956/58 to 1966. At Piarco however, the fluctuations and trends in the mean daily maximum temperature are in harmony with those of the mean annual temperature of the whole island. To verify the overall warming trend referred to previously, compensatory fluctuations in the mean daily minimum temperature at both stations was a logical phenomenon to investigate. Theoretically as the mean annual temperature increased between 1944 and 1956/58, and the mean daily maximum temperature decreased, there ought to have been

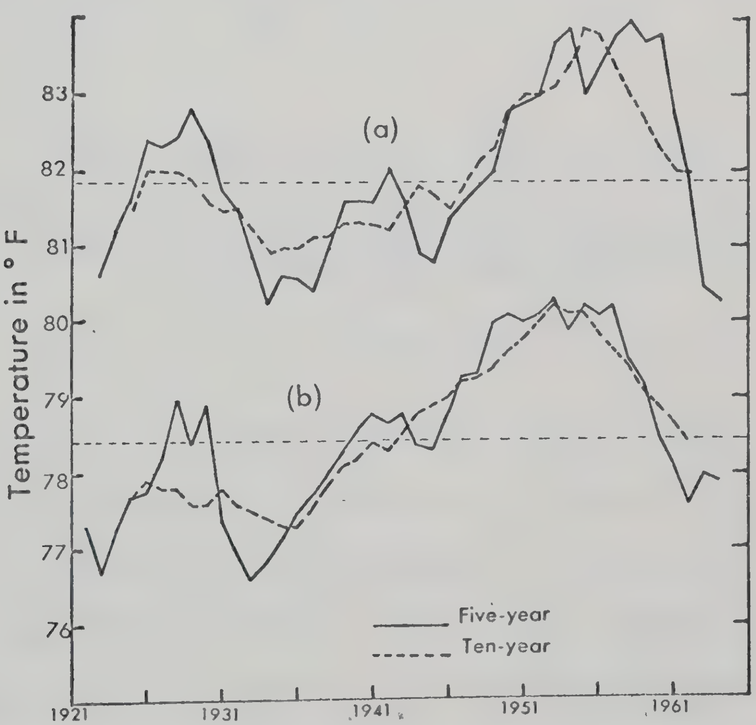
a rise in the mean daily minimum temperature. Similarly, in the period 1956/58 to 1966, when the mean annual temperature trended downwards, and the mean daily maximum trended upwards, the mean daily minimum should show a decreasing trend. It must be noted however, that during the warming period and up to about 1950 at St. Clair, the mean daily maximum temperature was well above the mean of 89.6°F. for the whole period reaching a peak of 92.3°F. in 1944. At Piarco, it remained above the long-term mean of 87.7°F. up to about 1960.

That there has been any significant upward trend in the mean daily minimum temperature at these two stations is not borne out by the curves of five and ten-year cumulative means (Figures 17 and 18). At both stations the curves fluctuate but with amplitudes of less than 1°F. above or below the means of 70.8°F. and 71.4°F. for St. Clair and Piarco respectively, except after 1957 when they took a relatively precipitous dip of 4.2°F., which fits well with the cooling trend in the overall mean annual temperature curve. While therefore, the fluctuations in the mean maximum temperature are apparently significant numerically, those in the mean minimum are not.

Lamb and Johnson (1959), found that rises of mean temperatures from thirty-year periods in the middle to late nineteenth century to the warmest period of the early to mid-twentieth century were significant at or about the one per cent level at most places tested including Trinidad. The

evidence assembled in the present investigation shows also a rise in the mean temperature.

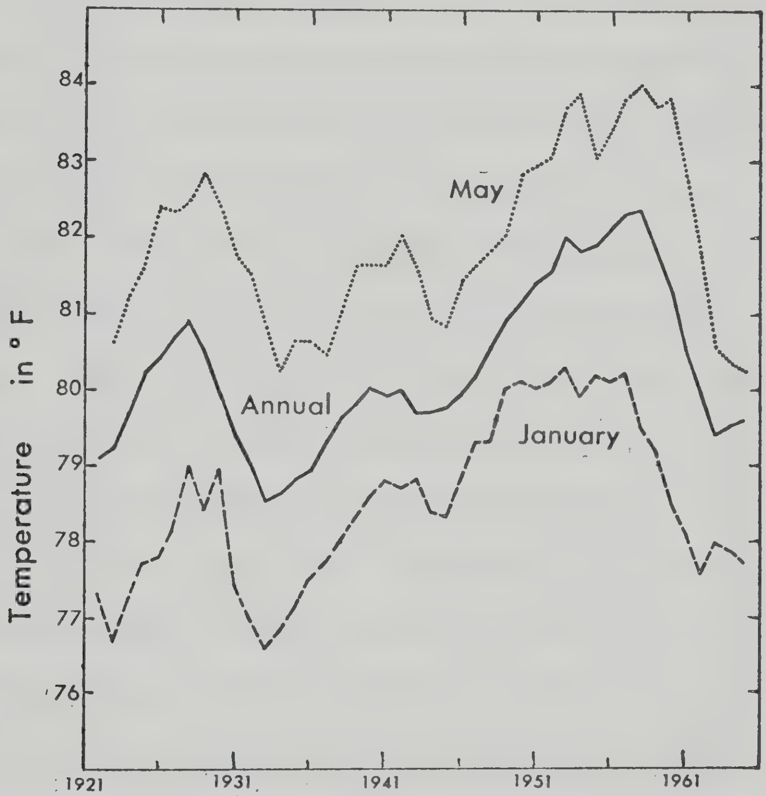
Isolating that component of the mean annual temperature that contributed most to the general rising temperature trend indicated in the records proved to be a difficult exercise. As has been indicated, the mean daily maximum temperature and the mean daily minimum temperature figures for two stations provided no decisive answers. It was therefore decided to examine the mean January and mean May temperatures for the period 1921-66, since these months were shown to be the coolest and warmest respectively. Five and ten-year cumulative means are calculated. The curves appear in Figure 19. There are no characteristic differences between these



Cumulative means of monthly mean temperature; (a) May, (b) January.

Figure 19

curves and those of the mean annual temperature. They are plotted together in Figure 20 to facilitate comparison. The trends are very similar. It is therefore difficult to say



Comparison of Five-year cumulative means of Mean Annual, Mean January and Mean May temperatures, for Trinidad (1921-1966).

Figure 20

which component changed relative to the others, if in fact such a change did occur. What-ever changes there may have been have occurred simultaneously in the maximum, minimum and seasonal temperatures. Again, the general trend has been one of rising temperature, although fluctuations are superimposed on this upward movement. The crests of the

major fluctuations tend to be much more above the mean of the whole period than the troughs are below it. This is evident in all the temperature components examined--annual, maximum, minimum and seasonal. It is therefore possible that the rise of 4.8°F. during the period of maximum warming compensated to a large extent for the early régime when mean annual temperatures were below the mean of the whole period.

That there was an undoubtedly significant warming trend up to about 1958 in Trinidad, West Indies is quite apparent. Also undeniable is the fact that this trend was reversed soon after 1958 and has continued up to the end of the period under inquiry. The reversal represents a temperature decrease of about 3°F. Student's t test on the significance of the difference between the means of 1921-33 and 1934 to 57 and between that of 1934 to 1957 and 1957 to 1966 for mean annual temperature was significant at better than the 95% confidence level.

The causes of these fluctuations and trends are beyond the scope of this study, but it is difficult, in the light of the discussion so far to escape the tentative conclusion that the warming trend was probably a function of increased solar radiation or alternatively an increase in the absorption effectiveness of incoming solar radiation. It will be shown later that the transparency hypothesis is feasible, for the period of greatest warming was a period of decreased precipitation and presumably reduced cloudiness. It must be borne in mind however, that the "mean" over a

time period formed the basis of this analysis, and that these statistics place some limitations on the conclusions that one can safely draw. However, the aim of this study is not to ferret out causes of fluctuations, but to verify whether fluctuations have in fact occurred over the period.

CHAPTER IV

TIME-SERIES ANALYSIS OF PRECIPITATION

In this section the results of investigations into fluctuations and trends in rainfall for the same period as temperature are presented. It has been pointed out that a study of long-term rainfall data should give an indication of the presence or absence of climatic fluctuations and changes in a given locality. For most of this section reference will be made to the significance of observed fluctuations and trends in purely statistical terms, but it must be remembered that fluctuations may be assessed as significant from other points of view. An example is that of the biological effects observed. On this view, inferences are made that a significant climatic change has occurred if the type of weather has so far altered in an area that the composition of the vegetation, the régime of the water budget, practices of cultivation and ultimately the fauna are measurably changed. It is therefore possible to have fluctuations that were not statistically significant but which may have had some noticeable effect on the environment or the way of life of the inhabitants.

In oceanic locations where the variations of temperature and moisture levels and the associated atmospheric stability and instability cause mostly all the rainfall, the

fluctuations in precipitation should provide a sensitive index of the presence, and possibly the primary causes of climatic fluctuations. Mention was made earlier of the fact that there are topographical influences on the rainfall distribution of Trinidad; it must be emphasized that the orientation of the mountain belts tends to minimize the extremes of rainfall which can be typical of some Caribbean islands where the windward stations receive high totals and the leeward stations low ones. This writer recognizes that distributions of this kind could affect the island's mean especially if there is a bias in favour of stations experiencing one or the other extreme in the sample. This bias does not occur, for when reference is made to the mean rainfall of the island, the value given is in fact the mean of all reporting stations, and these are fairly evenly distributed throughout the island as Figure 1 shows. In addition, the stations chosen for individual analysis represent as far as is possible typical rainfall distribution types. Also,mention has previously been made about the contribution that hurricane precipitation makes to the monthly and annual totals.

The mean annual rainfall of the island as derived from the data under review is 76.0 inches, of which 59.4 inches occur in the wet season, June to December and 16.6 inches in the dry season, January to May. Taken as a whole, the island receives 78.2% of its precipitation in the rainy

season as against 21.8% in the dry season. The characteristics of the rainfall are set out in Tables 4, 5 and 6. Not

TABLE 4

TRINIDAD RAINFALL, 1921-66. JANUARY TO APRIL, AND JANUARY TO MAY

	Jan.	Feb.	Mar.	April	Jan.-April	May	Jan.-May
Mean (ins.)	3.9	2.7	2.2	2.8	11.6	5.0	16.6
Mean as % of annual	5.1	3.6	2.8	3.7	15.2	6.5	21.8
Median (ins.)	3.3	2.0	2.0	2.3	9.6	4.3	13.8
$\frac{\text{Mean-Median}}{\text{Mean}} \times 100$	15.2	26.9	7.4	19.4	17.4	14.4	16.5
Highest as % of mean	253.	513.	252.	360.	334.	245.	307
Lowest as % of mean	34.4	2.9	8.3	15.5	17.1	20.5	18.4
Coefficient of Variation (%)	55.0	92.0	69.2	74.0	70.9	57.2	66.8

only is Trinidad's annual rainfall characterized by wide variations in spatial distribution, but the variations from year to year are also relatively large. Figure 3(a) shows that north-eastern stations record means of greater than 130 inches while south-western stations record means of between 50 and 60 inches. The physical orientation of the island in relation to the prevailing North-east Trade winds explains this distribution to a great extent.

Taking the coefficient of variation as a measure of variability, we note that its value ranges between 16 and 23 per cent over large parts of the country for mean annual

TABLE 5

TRINIDAD RAINFALL, 1921-66. JUNE TO NOVEMBER AND JUNE TO DECEMBER

	June	July	Aug.	Sept.	Oct.	Nov.	June - Nov.	Dec.	June - Dec.
Mean (ins.)	9.5	9.6	9.6	7.4	7.1	8.5	51.7	7.5	59.3
Mean as % of annual	12.5	12.6	12.7	9.8	9.3	11.2	68.1	9.9	78.1
Median (ins.)	9.3	9.1	9.6	7.4	6.9	8.7	50.9	7.6	58.5
$\frac{\text{Mean - Median}}{\text{Mean}} \times 100$	2.5	4.8	0.8	0.9	2.4	-2.0	1.6	-1.3	1.3
Highest as % of mean	181	143	154	152	143	176	159	164	160
Lowest as % of mean	35.0	58.5	51.5	48.5	50.6	30.5	45.7	32.8	44.0
Coefficient of variation (%)	34.7	22.7	20.1	26.4	25.5	28.7	26.3	32.9	27.1

precipitation. For the island as a whole this represents a variation of 59 to 141 per cent in the mean annual rainfall. A realistic approach, is to examine not only the annual variability but also the seasonal variability for the island as a whole and then for representative stations. Garstang (1959) concluded that April and May, and November and December were transitional months in terms of rainfall incidence and he went on to say that "whereas the departures from the mean during the mid-wet and mid-dry period are relatively small, they are greatest during the transitional periods." It was therefore felt that dividing the year into a dry season, January to April, and a wet season, June to November and then comparing their variability with January to May and June to December would assist in showing to what extent these months contributed to the variability of each season.

Over 78% of the mean annual rainfall is received in the period June to December. The lowest percentage rainfall received by any one place in any one of these months is 9.3% while the highest is 12.7%. The variability ranges from 44% to 160% of the mean. The coefficient of variation is 27.1%. December contributes an average of 9.9% of the mean annual rainfall and its totals vary from 33% to 164% of its mean. November contributes 11.2% and its totals vary from 30.5% to 176% of its mean for a coefficient of variation of 29%. In addition, December's average coefficient of variation of 33% is exceeded only by June, 35%. When however, the period June to November is considered, the coefficient of variation of

TABLE 6

COEFFICIENT OF VARIATION (%): MONTHLY VALUES

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
THE WHOLE ISLAND												
Mean (ins.)	3.9	2.7	2.2	2.8	5.0	9.5	9.6	9.7	7.4	7.1	8.5	7.5
Coefficient of variation (%)	55.0	91.8	69.2	74.0	57.2	34.7	26.7	20.1	26.4	25.5	28.7	32.9
ST. AUGUSTINE												
Mean (ins.)	2.7	1.6	1.1	2.0	4.6	8.9	8.8	9.3	7.5	6.1	7.5	5.8
Coefficient of variation (%)	66.3	127.6	97.3	94.2	73.6	37.6	31.3	30.4	39.0	37.5	36.1	43.9
ST. MADELEINE												
Mean (ins.)	3.1	1.9	1.5	2.3	4.2	8.3	8.5	9.0	7.0	6.8	7.2	6.7
Coefficient of variation (%)	61.8	110.2	101.	83.9	59.7	36.1	33.5	36.1	38.7	46.7	32.8	49.0
ST. CLAIR												
Mean (ins.)	2.5	1.6	1.7	2.3	3.4	6.9	8.3	9.6	8.0	6.6	7.6	5.2
Coefficient of variation (%)	62.4	113.9	80.8	96.1	78.8	38.5	29.0	28.3	31.6	37.6	33.3	41.0
MORUGA												
Mean (ins.)	4.1	2.3	1.5	2.2	5.1	9.3	8.1	7.8	6.5	6.2	7.9	8.7
Coefficient of variation (%)	66.1	106.5	80.3	90.3	52.9	47.9	40.5	28.8	63.0	67.8	39.3	54.5
CARONI												
Mean (ins.)	2.9	1.6	1.3	2.1	5.5	10.3	9.9	10.4	8.5	7.1	7.9	6.4
Coefficient of variation (%)	73.5	167.1	116.1	94.8	68.7	41.6	28.4	33.2	33.2	42.3	49.6	51.0

TABLE 6 continued:

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
MAYARO												
Mean (ins.)	5.1	2.9	2.2	2.6	5.5	10.2	8.9	9.4	6.8	6.7	9.3	9.6
Coefficient of variation (%)	64.1	101.2	99.0	99.3	59.9	40.6	32.8	36.0	47.4	34.1	33.9	37.3
COUVA												
Mean (ins.)	2.9	1.7	1.3	2.1	4.1	8.5	8.8	9.2	7.7	6.4	7.2	6.1
Coefficient of variation (%)	68.4	114.6	96.4	112.3	58.8	47.7	27.3	31.1	28.9	45.4	37.2	40.7
POINT FORTIN												
Mean (ins.)	4.2	2.7	3.2	4.0	5.1	9.2	11.0	11.2	7.5	8.1	8.3	7.5
Coefficient of variation (%)	58.3	103.2	93.6	65.9	66.5	37.2	31.8	22.2	34.3	33.6	37.8	40.4
TAMANA												
Mean (ins.)	5.8	3.9	2.8	3.5	6.7	12.7	12.2	11.5	9.4	9.0	10.6	11.7
Coefficient of variation (%)	60.6	94.4	80.5	92.1	49.0	36.9	33.4	32.9	37.5	41.0	38.9	47.5

far removed from that of 27.1% for June to December, and the variability range of 46% to 159% of the mean is not vastly different. It is therefore evident that, taking the island as a whole December makes only a small contribution to the variability range of rainy season rainfall. For the wet months June shows the highest coefficient of variation with December and November following in that order. If however, individual stations are taken as is shown in Table 6, December emerges as the month with the highest coefficient of variation among the wet months, and could therefore be characterized as the transitional month between the rainy season and the dry season.

During the dry season the percentage rainfall received at any one station is low, no one month exceeding 7% of the mean annual total. The dry season is characterized by remarkable variability. If the period January to April is considered, the mean rainfall for that period is 11.58 inches. This represents 15.2% of the mean annual rainfall. What is remarkable, however, is the fact that it is possible to receive anywhere from 17% to 334% of the mean in any one year, or in terms of inches, between 1.97 and 38.7 inches. The coefficient of variation is 71%. When the individual months are considered the coefficients of variation read 55%, 92%, 69% and 74% for January to April respectively. February presents the greatest variability with figures of 3% to 513% of its mean of 3.56 inches, and April 15% to 360% of its

mean of 3.73 inches.

When May is added to this period, the coefficient of variation drops to 67% indicating that May exhibits relative reliability in terms of its rainfall expectation. January to May contribute 21.8 inches to the mean annual rainfall, May itself contributing 6.5 inches with a coefficient of variation of 57%. Its variability ranges from 20% to 245% of its mean, the lowest range for the five months. It is here that these results diverge from the findings of Garstang. It is evident that from the data examined, January to April can be considered the "real" dry season and June to November the rainy season. It must be acknowledged however, that a minimum in the wet season rainfall exists in the month of November. Also, the variability of dry season rainfall is high in most areas and particularly in the leeward, western section of the island.

In order to give a spatial dimension to rainfall variability, nine stations were chosen for analysis. The choices were based on the length of available records and on their reliability. Also, these stations were selected as representative of particular régimes within the island--the relatively wet eastern section and the drier western sections. While the number of stations was inadequate to draw reliable maps of coefficients of variation, the numerical values seem sufficient to give some indication of variability in the spatial sense. Table 7 gives some values of coefficients--annual and seasonal.

TABLE 7

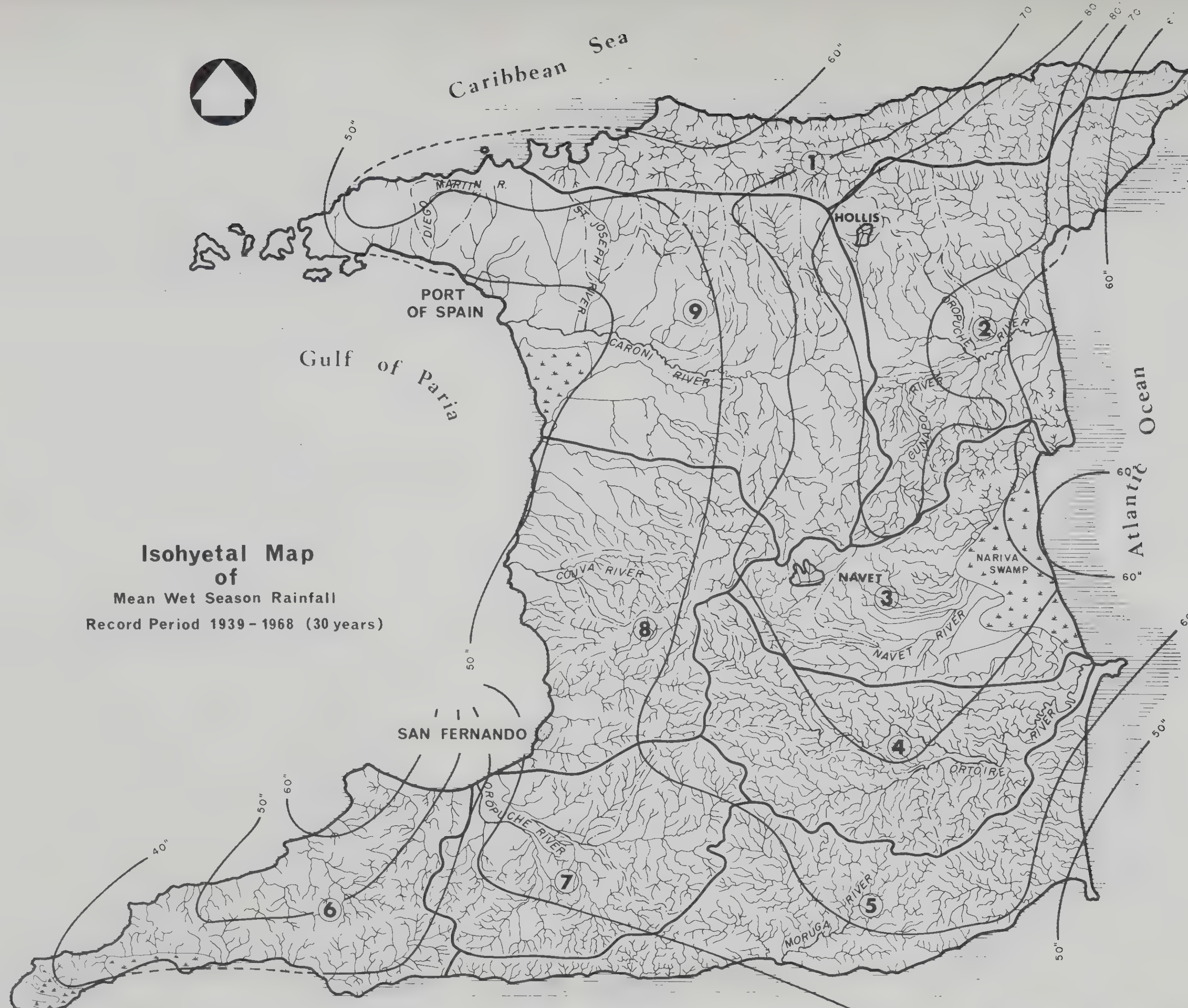
COEFFICIENTS OF VARIATION FOR NINE STATIONS BY SEASONS

	ANNUAL			RAINY SEASON			DRY SEASON		
	Mean ins.	σ ins.	Coeff. of var. (%)	ins.	σ ins.	Coeff. of var. (%)	ins.	σ ins.	Coeff. of var. (%)
Trinidad (as a whole)	75.97	12.07	15.88	51.71	7.01	13.56	11.53	5.83	50.62
St. Clair*	63.64	11.60	18.23	47.00	7.60	16.16	8.07	5.19	64.28
Usine St. Madeleine*	66.45	12.13	18.25	46.79	8.03	17.16	8.81	5.39	61.21
St. Augustine*	65.96	12.52	18.97	48.10	8.31	17.26	7.42	5.03	67.81
Moruga	69.79	15.18	21.75	46.91	12.62	26.90	10.10	5.78	57.29
Caroni (Fredericks Estate)*	73.75	15.23	20.65	54.36	10.55	19.40	7.76	6.16	79.28
Point Fortin	81.94	14.77	18.02	55.36	7.92	14.30	14.04	8.52	60.68
Tamana	99.42	21.91	22.04	65.37	12.91	19.75	15.92	9.92	58.33
Perseverence Est. Couva*	66.16	12.06	18.23	47.91	7.84	16.38	7.99	5.70	71.29
Mayaro	79.38	18.16	22.87	51.37	9.53	18.55	12.86	8.38	65.19

*"Dry zone" stations

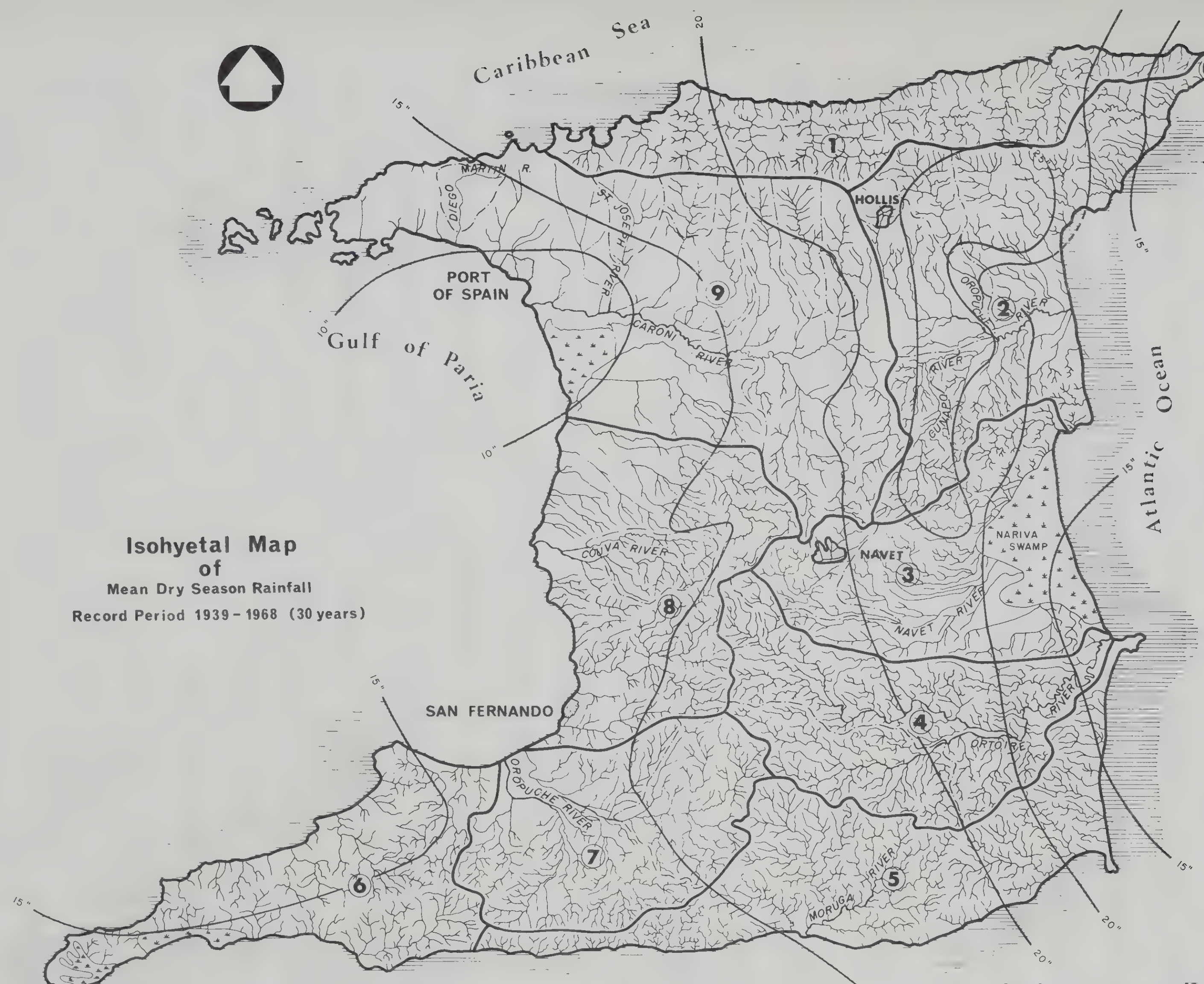
When the annual rainfall totals are taken the coefficients of variation in space show very marginal differences ranging from 18% in Point Fortin in the western section of the island to 22% in Tamana and 23% in Mayaro in the east. The dry season figures however, are more revealing. The highest coefficients of variation are found in the west and southwest and the lowest in the east. The lowest figures being those of Moruga, 57.3% and Tamana, 58.3% while the highest values are found in Caroni and Couva--79.3% and 71.3% respectively. The wet season figures are almost similar to those of the annual. During the dry season the most important mechanism involved in rainfall distribution is advection showers that develop off or over the east coast and are subject to orographic lifting, therefore the penetration of showers decreases progressively from east to west across the island. Figures 21 and 22 show the mean seasonal distribution of rainfall for the period 1939 to 1968.

In a preliminary enquiry into the fluctuation of rainfall in time, the utilization of cumulative means is conceivably adequate to identify fluctuations in precipitation. However, cumulative means in a time series do possess some disadvantages in that they obscure the time when a trend changes, and may be misleading in the not infrequent case of the single exceptionally wet or exceptionally dry year affecting the long-term mean. Also it can be argued that the cumulative average applied to a random series gives rise



Reproduced from Water Resource Survey (1967)

Figure 21



Reproduced from Water Resource Survey, (1967)

Figure 22

to a series which is no longer random in character (Grant, 1952). Runs of short length are suppressed both in number and amplitude while runs equal to the period of the cumulative means are increased in number. Also, running means may cause serious phase errors for fluctuations of the order of the mean. Nonetheless as a first approximation the method is useful in that some indication is given of fluctuations that occur.

In the light of this therefore, additional methods will be applied in the hope that they will reinforce one another, and lend greater validity to the conclusions arrived at. One such method is cumulative percentual deviation from the mean. Abrupt changes do not show up well in a time series graph of annual or seasonal rainfall totals, but as Kraus (1955) points out, it is a valuable property of cumulative residuals that any change in a time series is often immediately apparent from the resultant graph. Gregory (1968) supports this view. Cumulative percentual deviations from the mean of Trinidad's annual and seasonal rainfall, to which reference will be made later were calculated by first determining the mean for the whole period under consideration, both for the annual and seasonal totals. This value was then subtracted from each annual and seasonal rainfall total in turn and running totals of the residual so computed were then plotted. This is expressed symbolically as:

$$\frac{\Sigma(x - \bar{x}) \ . \ 100\%}{\bar{x}} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad (6)$$

where $\bar{x}$ is the mean and x the rainfall occurrence at time t. This is done for the island as a whole and for three stations within the island--St. Clair, St. Augustine and St. Madeleine. It was felt that, as the annual totals for the island as a whole were composed of the monthly means of all reporting stations, the overall averaging of data from relatively wet areas and relatively dry ones presented a situation that was unrealistic. Percentual deviations are used instead of simple residuals so as to make records of differing regimes comparable on the same scale.

In view of the remarks by Barnard (1956) and O'Carrol (1956), it should be stressed that the graph of cumulative percentual deviations was used only to indicate the periods of greatest deviations and probable fluctuations in the series. It will be seen later that statistical tests of significance are applied to the annual and seasonal rainfall totals and not to the residuals from which Figures 16, 17 and 18 were drawn. Both Barnard and O'Carrol think too, that if the sub-periods indicated by the graph of $\Sigma\frac{(x - \bar{x}) \cdot 100\%}{\bar{x}}$ are used for statistical analysis, a bias is introduced since these periods would have respective mean levels as different as possible and consequently greater than would have been expected among sub-samples chosen at random. This objection is statistically valid, yet it seems reasonable to expect that since the presence or absence of fluctuations and changes in the series is what is sought, a method that

indicates this is desirable, so long as the significance of these changes is not deduced therefrom. To meet the above statistical objections however, sub-periods indicated on the graphs together with other sub-periods chosen at random were statistically analyzed.

The method used here is the comparison of means of different periods, and the statistical t test of significance is employed. An attempt is made to test whether the mean of a sub-period was significantly different from the mean of the whole period under review. It is reasoned that if x_k is the mean of the first k years then $x_k = \frac{1}{k}\sum_1^k x_r$ and $\bar{x} = \frac{1}{n}\sum_1^n x_r$ where $\bar{x}$ is the mean of the entire period under consideration, then it is shown that $t = \tau_k\{k(n-2)/n-k-k\tau_k^2\}^{1/2}$ where $\tau_k = \frac{\bar{x}_k - \bar{x}}{s}$ is distributed as Student's t with n-2 degrees of freedom, and s is the standard deviation of the entire series. Also, sub-periods are compared with each other using the relation:

$$t = \frac{|\bar{a} - \bar{b}|}{\sqrt{\frac{S_a^2}{n_a} + \frac{S_b^2}{n_b}}} \quad \text{with } (n_a + n_b - 2) \text{ degrees of freedom} \quad \ldots\ldots\ldots \quad (7)$$

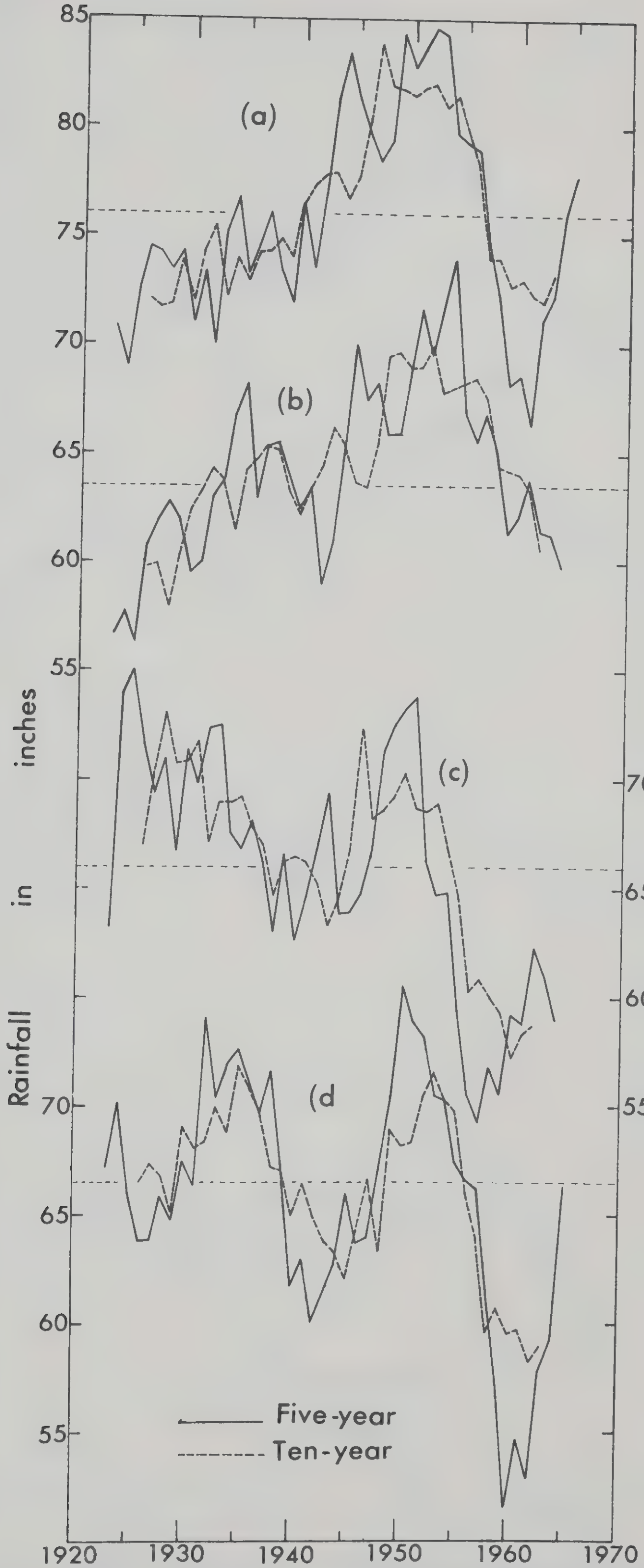
where $\bar{a}$ and $\bar{b}$ are the means of the sub-periods being compared, S_a^2 and S_b^2 their respective variances and n_a and n_b the number of years in the periods.

METHOD 1: CUMULATIVE MEANS

Five and ten-year cumulative means of rainfall totals for Trinidad, St. Clair, St. Augustine and St. Madeleine were

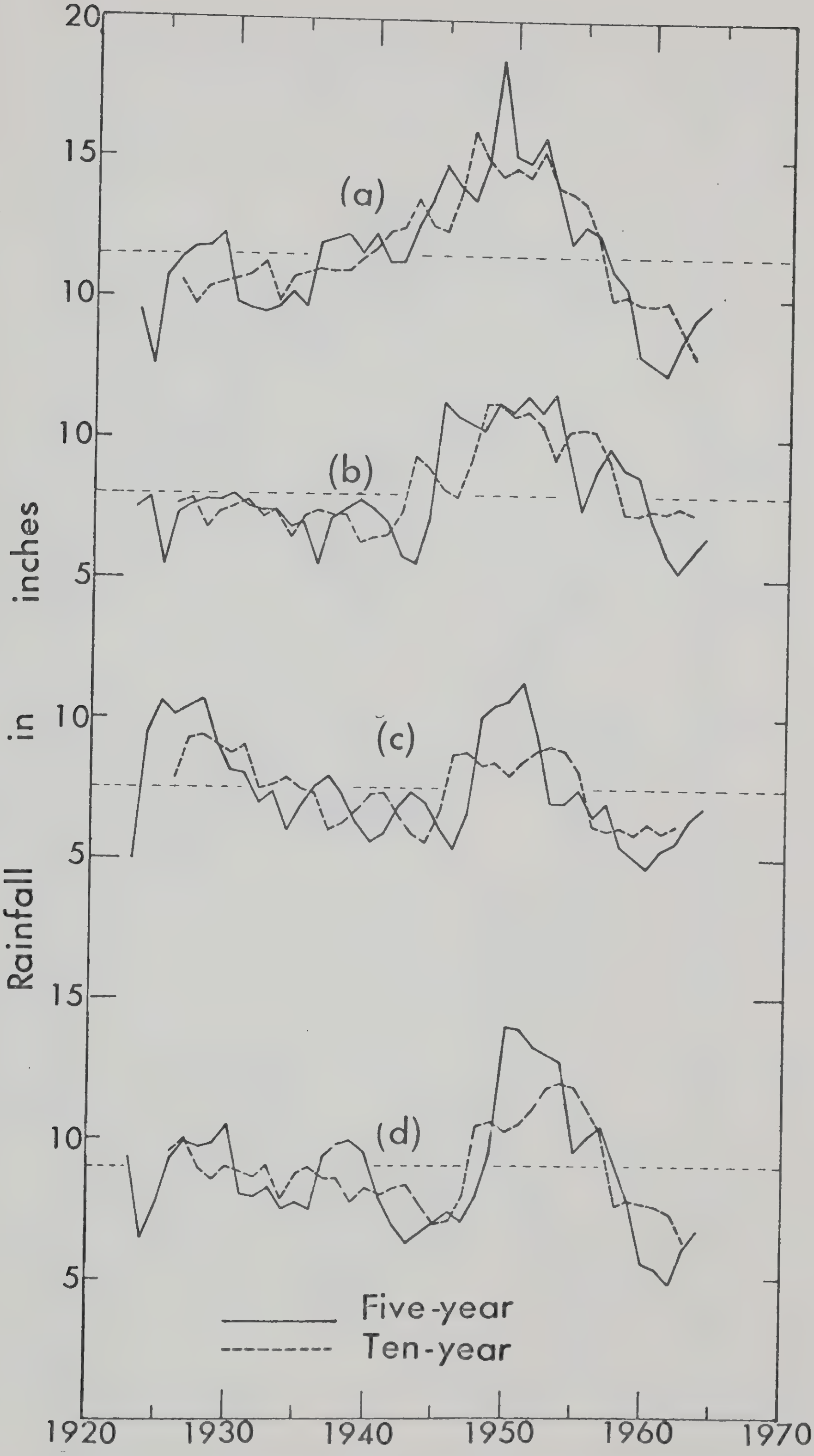
calculated and graphed for annual totals and for the dry and wet seasons respectively. These are shown in Figures 23, 24 and 25. The graphs of annual totals (23a) for the whole island indicate that there has been a varying but nonetheless rising trend from 1921 to about 1951-52, and a decreasing trend thereafter up to about 1961 followed by another rise. These fluctuations however, are not parallel at all stations. The rising trend from 1921 to about 1950-52 is also marked in the graphs for St. Clair (23b). At St. Augustine, there seems to have been a decreasing trend from 1925 to about 1940, an increase to about 1951, a decrease thereafter to around 1957, followed by another rise. At St. Madeleine, fluctuations were greater in number. There was a rise to about 1932, a decline to about 1942, another rise to 1950 followed by a decrease to 1960 and another rise thereafter. At all stations marked oscillations of about four to five years' duration are superimposed on the general trends.

The graphs for the dry season (Figure 24) indicate that the short period oscillations referred to above dominate the picture, but it is still possible to recognize the same general trends that showed up in the graphs of annual totals. The amplitudes of the fluctuations in the dry-season graphs however, are much less. The island as a whole showed a slightly increasing trend of dry season rainfall from 1921 to about 1949, a decreasing trend up to about 1961 and a rise thereafter. The St. Clair figures show parallel trends except



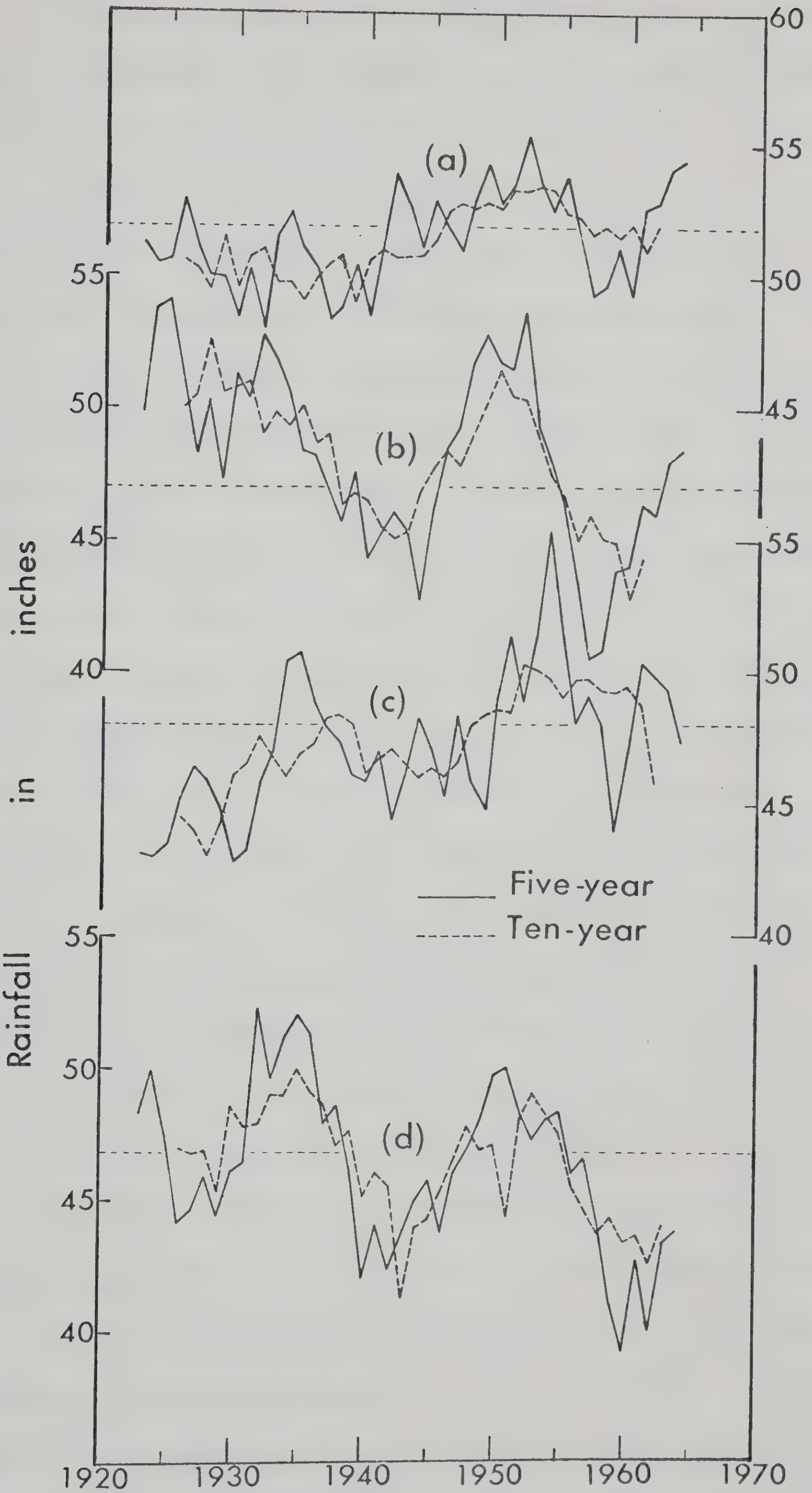
Five and ten-year cumulative means of annual rainfall for (a) Trinidad, (b) St Clair, (c) St Augustine and (d) St Madeleine, 1921-66.

Figure 23



Five and ten-year cumulative means of dry season rainfall for (a) Trinidad, (b) St Clair, (c) St Augustine and (d) St Madeleine, 1921-66.

Figure 24



Five and ten-year cumulative means of wet season rainfall for (a)Trinidad (b)St Clair (c) St Augustine and (d)St Madeleine, 1921-66.

Figure 25

for the years 1945-53 when the graphs levelled out somewhat. At St. Augustine, dry-season rainfall showed a decreasing trend from 1925 to around 1946, then a sharp increase to around 1952. This was followed by a decreasing trend which seems to be continuing. The same is true of St. Madeleine where the changes in trend seem to lag by two to three years.

The graphs of cumulative means of wet season rainfall (Figure 25) are more difficult to interpret. The oscillations are more marked and the trends are masked somewhat by these oscillations. However, as a first approximation it is safe to say that in Trinidad as a whole the wet season tended to become slightly wetter between 1921 and 1952, slightly drier between 1953 and 60, but is showing an upward trend since 1960. This is also true at St. Augustine. Wet season rainfall at St. Clair, on the other hand decreased to around 1944, increased to around 1953, plunged to its lowest in the five years following and is rising again. At St. Madeleine there were two distinct fluctuations each incorporating a rise and a fall. The first lasted from 1921 to around 1940 and the other from 1941 to around 1960. Rainfall increased in the periods 1921-32 and 1940-51, decreased in the periods 1933-40 and 1952-60. It is now on the upward swing again.

It is difficult to generalize on the basis of these graphs of cumulative means. There are both space and time shifts and these are most certainly tied in with the mechanisms that are responsible for the amounts and distribution

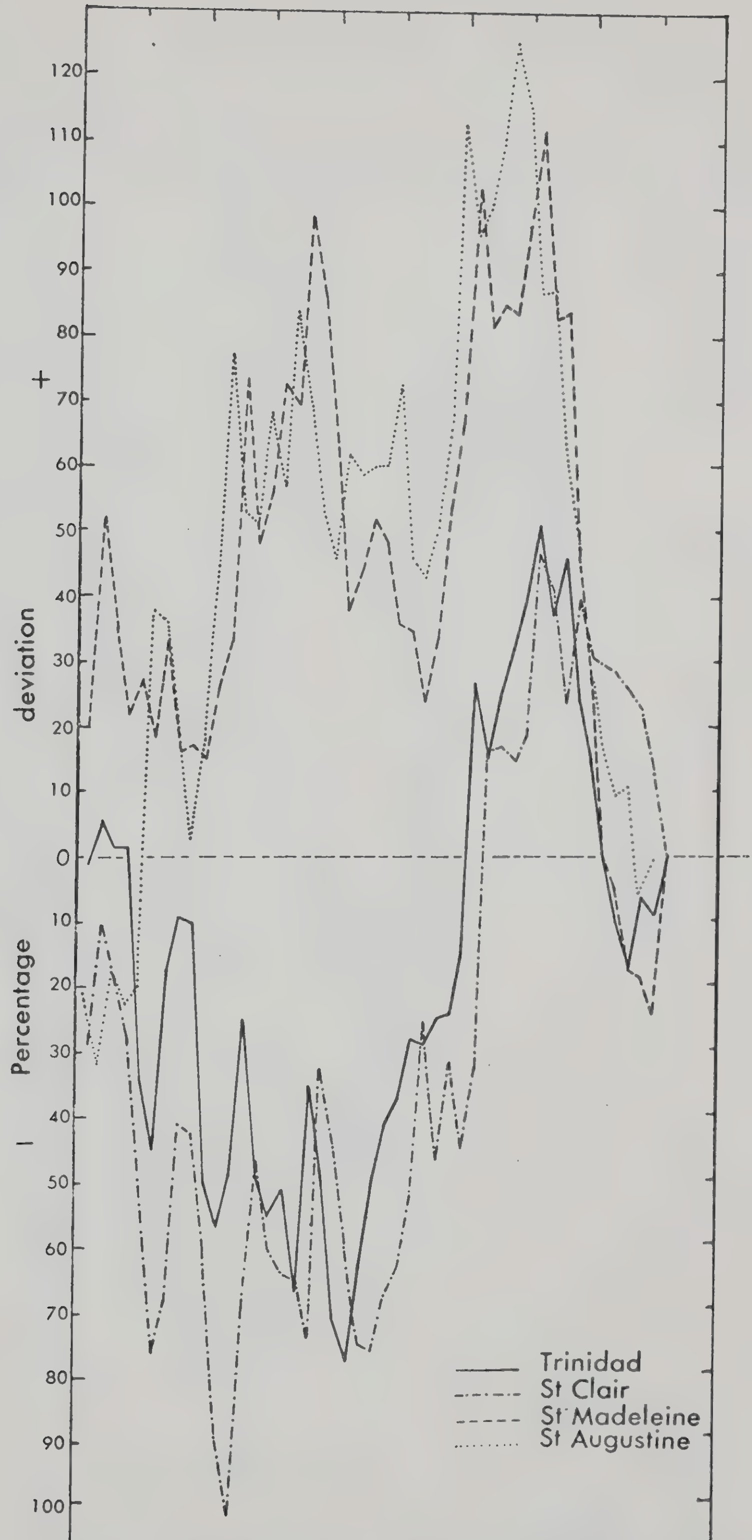
of rainfall in the island. These mechanisms have not yet been definitely identified and therefore the causative factors are still unknown. That there have been fluctuations over and above the short term variations cannot be denied, but these have not been concurrent in space, and to a great extent neither completely similar in time nor direction. The fluctuations do not seem to conform to any definite cyclic pattern, nor is the period between rises and falls anywhere near uniform. It is probable that if more stations were taken some grouping of régimes would emerge showing trends that were characteristic of regions within the island, but the varying lengths of available records militate against this approach.

Yet it is relatively safe to conclude that at the majority of stations examined not only has the dry season rainfall remained generally below the long term mean for most of the period under review, but there has been a general trend towards increased aridity from 1921 to around 1944 to 46. The dry season rainfall totals increased from 1944/46 until around 1950/53 when a decreasing trend again set in. What is more significant is that this last decreasing trend which is still continuing, has taken the rainfall of this particular season lower than it has ever been during the period 1921-66. In terms of wet season rainfall it can be said that there have been two major periods involving two phases of decreases and two of increases. The crests of the

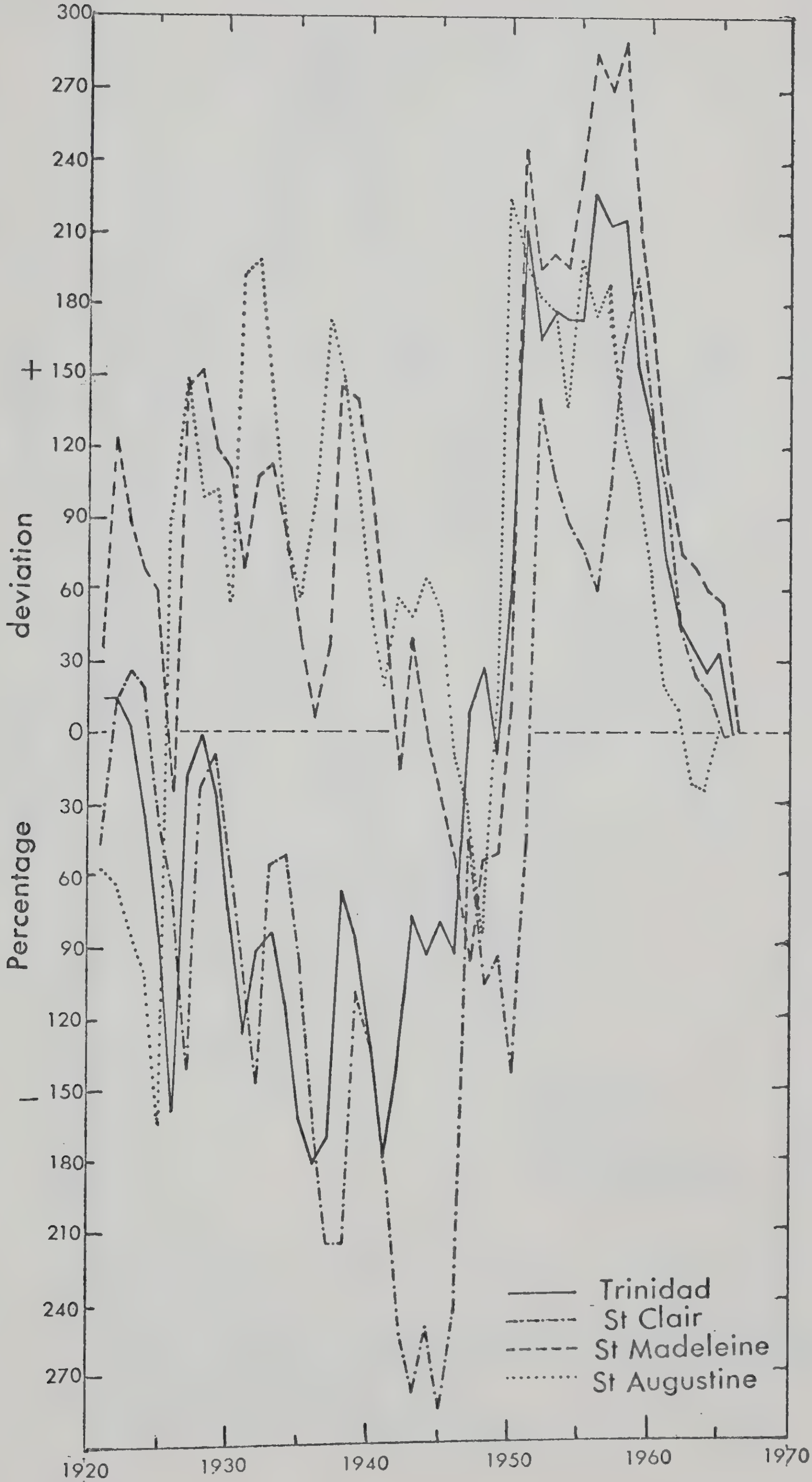
fluctuations occurred on the average twenty years apart while the troughs showed a recurrence interval of between fifteen to twenty years at all stations.

METHOD 2. CUMULATIVE PERCENTUAL DEVIATION FROM THE MEAN

Figures 26, 27 and 28 show the cumulative percentual deviations from the mean of annual, dry season, and wet season rainfall respectively. As was previously done, the island is considered as a whole and three other stations selected from within the island are taken for comparison. The graphs are here used to represent the changes that have taken place with time and to compare fluctuations that have occurred among stations within the study area. It must be stressed at the start that actual position on the graph is irrelevant with respect to any interpretation being made in terms of rate and direction of change. The significant features are the direction and angle of slope of the graph. Wherever this rises it indicates an increase in values while the more steeply it rises the more rapid and marked that increase is. Equally, however, if the rate at which the line falls becomes less, then this indicates an increase in values even though such increased values are still below the mean itself. Clearly, the date at which a series of below-average conditions is replaced by a series of above-average conditions can readily be appreciated. In all the graphs presented the significance of the short period oscillations is clearly seen, and these, to a large extent, present a rather

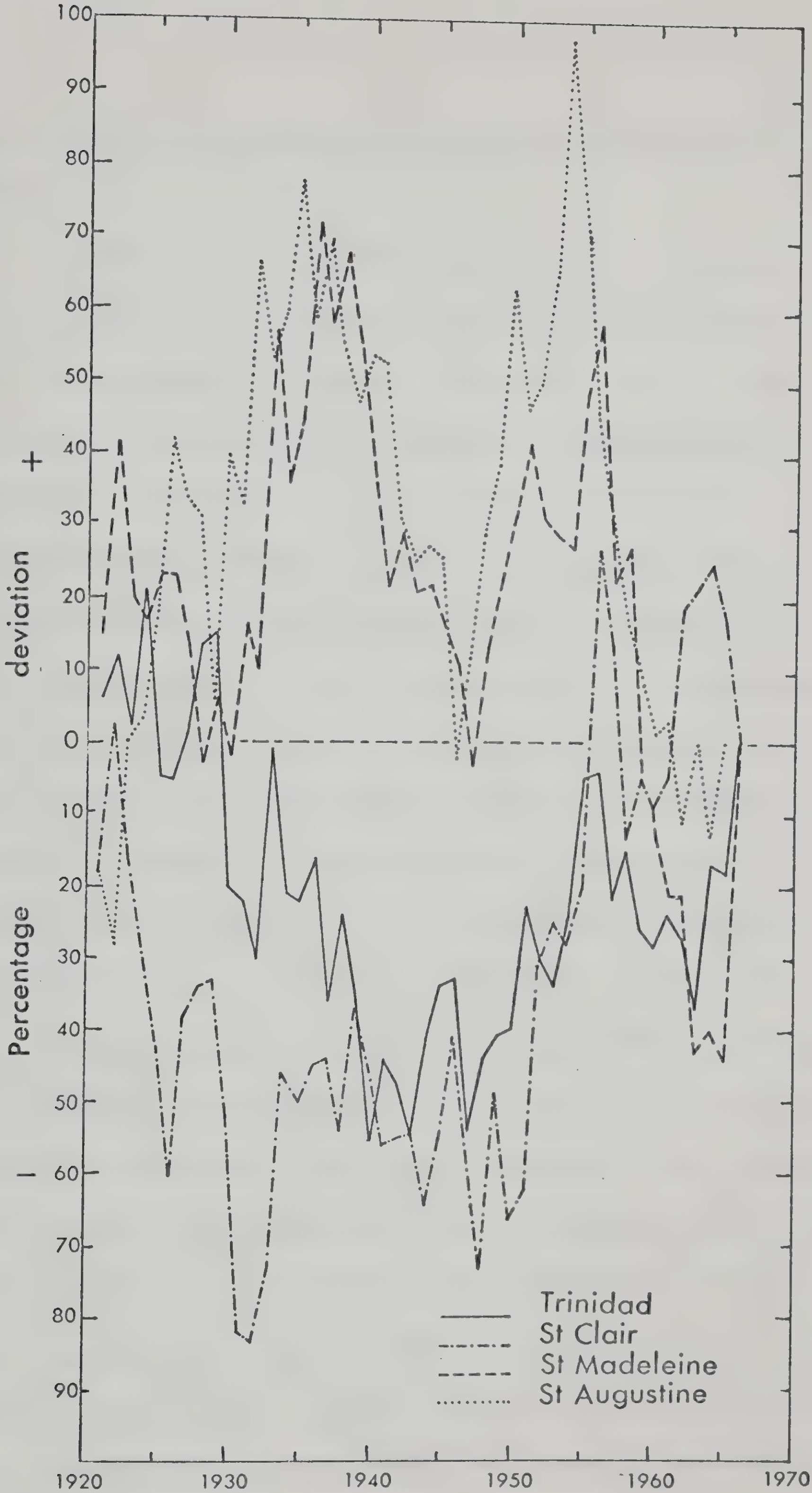


Cumulative percentual deviation from the mean of Annual rainfall of Trinidad, West Indies (1921–66) Figure 26



Cumulative percentual deviation from the mean of dry season rainfall (Jan—April), 1921—66

Figure 27



Cumulative percentual deviation from the mean of wet season rainfall, (June—Nov) of Trinidad, West Indies (1921—66)

Figure 28

erratic appearance to a graph that should be relatively smooth.

The graphs of deviations from the mean of annual rainfall, Figure 26, indicate that the four stations chosen fall into two distinct régimes--Trinidad and St. Clair showing one of these and St. Madeleine and St. Augustine the other. In the first of these it can be seen that a series of lower-than-average years extended from 1920 to 1941, followed by a series of above-average years up to 1956 at which time a decreasing trend began and is still continuing. In these two graphs rainfall is shown to have decreased between 1921 and 40 and 1956 and 66, but increased rapidly in the period 1941-55. The other régime is dominated by fluctuations of an average length of ten years. At St. Madeleine, rainfall increased from 1930 to 37, and again from 1947 to 56. Decreases were experienced in the periods 1921-29, 1938 to 46 and 1957 to 66. The St. Augustine graph is more difficult to evaluate due to the erratic nature of the short term variations. However, at this station there were rises from 1921-37, and from 1947-56 and decreases from 1938-47 and 1957-66.

The same two patterns are apparent in the dry season graphs, Figure 27. In the first of these two patterns, there is a fluctuating but markedly decreasing trend from 1921-41 in the Trinidad graph and from 1921 to 45 at St. Clair. This was followed by a rising trend which lasted up to 1957 in the Trinidad case, but up to 1959 at St. Clair. At both

stations a decreasing trend followed. At St. Madeleine, dry season rainfall decreased from 1921 to 47, increased to 1959 and then decreased again, while at St. Augustine the dry season became wetter between 1921 and 33, drier between 1934 and 48, and drier still thereafter.

An examination of the graphs of deviations from the mean of wet season rainfall indicates that the trends nearly parallel those of annual rainfall. Trinidad and St. Clair show decreases from 1921-47 and essentially rising trends thereafter. The curves for St. Madeleine and St. Augustine however, are much more complicated. At St. Madeleine, rising trends occurred in the following periods 1928-36, 1947-56 and decreasing trends during 1921-28, 1937-46 and 1957 to 66. At St. Augustine rising periods were 1921-35 and 1946-54 while decreases were shown in the periods 1936-45 and 1955-66.

Barnard (1956) indicated that changes that are immediately apparent on graphs of cumulative residuals may not be real or significant. It has been shown above that fluctuations in Trinidad rainfall are in fact apparent on the graphs presented here and that these fluctuations seem to follow a pattern. It was a basic understanding in the foregoing analysis that the graphs were indicators of fluctuations in so far as these were related to deviations from the long-term mean both in the negative and the positive sense. No conclusions as to the statistical significance of these fluctuations were drawn. This however, will be discussed in the ensuing section. The fluctuations indicated by this method do not seem

to be identical with those shown by the previous method in terms of the periods they cover or the years in which they change direction. This difference was not at all unexpected in the light of the discussions that preceded each method. However, the agreement is sufficiently close.

METHOD 3. COMPARISONS OF MEANS OF DIFFERENT PERIODS

The methods used in this section have been detailed earlier. Two different tests of significance are used. The first one was applied by Rao (1960) in his study "Climatic changes in India." The means of sub-periods are compared with the mean of the whole period with n - 2 degrees of freedom for Student's t test. This was deemed to be sufficiently stringent in a situation where the usual standard error of the difference becomes inoperable simply because the periods compared do overlap. In the other case the conventional statistical test for the significance of the difference between means is used as the samples are assumed to be independent of each other.

The means for the period 1921 to 1966 were prepared for nine stations in Trinidad. For each station the difference between the means of the sub-periods 1921-30, 1921-40, 1921-50 and 1921-60 respectively and that of the whole period was examined. The results are shown in Table 8. It is interesting to observe that for only two stations was the annual rainfall of the period 1921-30 significantly different

TABLE 8

COMPARISON OF MEANS OF DIFFERENT PERIODS WITH 1921-66, AND t VALUES: ANNUAL TESTS

STATIONS	Mean ins.	σ	Highest ins.	% of Means	Lowest ins.	% of Means	1921-30 minus 1921-60	t value	1921-40 minus 1921-60	t value	1921-50 minus 1921-60	t value	1921-60 minus 1921-66	t value
Trinidad	76.0	12.1	107.1	141.	45.3	59.6	-4.6	-1.13	-2.7	-1.35	-0.4	-0.3	0.3	0.4
St. Clair	63.6	11.6	95.1	149.	44.9	70.6	-3.8	-1.22	-1.1	-0.6	-0.1	0.1	0.9	0.5
St. Augustine	65.9	12.5	104.7	159.	47.5	72.0	0.2	-0.61	1.8	0.9	1.5	0.9	-0.9	-0.6
St. Madeleine	66.5	12.1	93.5	141.	42.0	63.2	1.0	0.3	2.1	1.0	1.5	1.1	0.5	0.7
Moruga	69.8	15.2	116.6	167.	43.7	62.6	1.9	0.4	1.7	0.7	2.6	1.5	2.3	1.2
Caroni	73.7	15.2	100.2	136.	48.2	65.3	-1.4	-0.4	1.0	0.4	3.9	1.6	4.1	1.2
Point Fortin	81.9	14.8	133.7	163.	63.8	77.8	7.9	2.0*	5.1	2.2	2.4	1.0	2.8	0.9
Tamana	99.4	21.9	158.9	160.	61.1	61.4	3.7	0.5	5.2	1.6	0.1	0.1	1.1	0.1
Couva	66.2	12.1	95.4	144.	47.0	71.0	-8.7	-2.7*	-2.1	1.2	-1.0	-1.0	-1.7	0.4
Mayaro	79.4	18.2	134.3	169.	56.5	71.2	-5.9	1.7	0.8	0.3	-0.3	-0.1	-0.8	0.2

* Significant at the 95% level.

at the 95% confidence limit from the whole period under review. The differences at all other stations for all the other periods failed to reach the 95% level. Student's t values ranged from 0.135 to 1.87. This analysis seems to suggest that there was no significant trend in the annual rainfall of the stations examined for the period 1921-66.

When however, decadal means are compared with the mean for the whole period, the first decade 1921-30 showed significant differences in the annual precipitation at two stations at the 95% level. None was significant in the period 1931-40, the second decade; two showed significance in the third decade 1941-50; one in the decade 1951-60 while almost all stations showed a significant change to aridity in the decade 1957-66. These results are shown in Table 9.

In Tables 10 and 11 decadal averages and values of t are given for the wet-season and the dry-season respectively. For the wet season Point Fortin shows significant changes in the decades 1921-30 (99% confidence limit) and 1931-40 (95% level). Change in Tamana was significant at the 95% level in the decade 1921-30 and in Caroni the decade 1941-50. St. Clair showed a significant change in the decade 1957-66. Almost all stations experienced a significant negative change in the decade 1957-66 in wet season precipitation totals. For the dry season, only in the decade 1957-66 was the difference of the means significantly different at the 95% level for most stations.

TABLE 9

COMPARISON OF DECADAL MEANS WITH MEAN OF 1921-66, AND t VALUES: ANNUAL TOTALS

STATIONS	1921-30		1931-40		1941-50		1951-60		1957-66	
	Mean	t Value	Mean	t Value	Mean	t Value	Mean	t Value	Mean	t Value
Trinidad	72.1	-1.13	74.2	-0.47	80.3	1.28	78.3	0.68	72.1	-1.14
St. Clair	59.8	-1.22	65.4	0.55	65.5	0.58	67.7	1.28	60.1	-1.12
St. Madeleine	67.4	0.29	69.7	1.35	66.6	-0.63	59.63	-2.06*	58.9	-2.48*
St. Augustine	66.2	0.61	69.2	1.37	66.9	0.24	64.7	-0.37	58.4	-2.26*
Moruga	71.7	0.40	70.5	0.16	73.9	0.87	-	-	58.8	-2.83*
Caroni	72.3	-0.37	76.6	0.60	83.6	2.53*	-	-	59.2	-4.00*
Point Fortin	89.8	2.03*	83.7	0.43	78.2	-0.91	-	-	71.9	-2.63*
Tamana	103.1	0.54	105.6	1.03	87.3	-2.00*	-	-	93.9	-1.02
Couva	57.5	2.71*	68.5	0.73	67.6	0.38	-	-	69.0	-0.84
Mayaro	73.5	-1.14	85.2	1.13	78.3	-0.04	-	-	75.9	-0.63

* Significant at the 95% level; - missing data.

TABLE 10

DECADAL AVERAGES AND VALUES OF t--WET SEASON

STATION	1921-30		1931-40		1941-50		1951-60		1957-66	
	Mean	t Value	Mean	t Value	Mean	t Value	Mean	t Value	Mean	t Value
Trinidad	50.64	-0.5	49.91	-0.9	52.49	0.4	52.30	0.3	51.93	0.1
St. Clair	46.71	-0.6	48.26	-0.2	46.63	1.2	49.75	0.7	41.63	2.6
St. Madeleine	46.69	-0.0	48.62	1.0	46.56	-0.1	44.67	-0.9	44.05	-1.9
St. Augustine	48.38	-1.3	50.10	1.1	47.74	-0.3	46.64	0.8	44.41	2.4*
Moruga	50.30	0.8	44.73	0.7	47.77	1.2	-	-	40.78	3.1**
Caroni	54.68	0.9	55.37	1.3	59.58	2.3*	-	-	48.35	2.7*
Point Fortin	61.78	3.2*	55.96	2.0*	51.47	1.6	-	-	54.32	1.9
Tamana	68.03	2.1*	66.88	0.3	58.16	0.8	-	-	67.11	2.0*
Couva	43.58	1.3	49.78	0.9	47.02	1.7	-	-	36.79	3.0**
Mayaro	50.32	1.7	51.42	0.8	50.90	0.5	-	-	52.87	2.0*

* Significant at the 95% level.
** Significant at the 99% level.

TABLE 11

DECADAL AVERAGES AND VALUES OF t--DRY SEASON

STATION	1921-30		1931-40		1941-50		1951-60		1957-66	
	Mean	t Value	Mean	t Value	Mean	t Value	Mean	t Value	Mean	t Value
Trinidad	10.60	-0.55	10.96	-0.34	13.73	1.35	12.27	0.45	8.90	-1.62
St. Clair	7.75	-0.61	7.27	-1.28	9.21	1.31	9.25	0.63	6.42	-1.81
St. Madeleine	9.81	9.65	8.69	-0.08	8.04	-1.11	10.24	1.55	6.28	-1.69
St. Augustine	8.26	0.83	7.44	-1.39	6.71	0.97	8.12	1.42	5.94	-2.81*
Moruga	8.78	0.76	11.35	1.64	10.85	0.62	-	-	7.85	-3.01**
Caroni	7.86	0.32	8.01	1.23	7.54	1.18	-	-	4.65	-2.73*
Point Fortin	15.23	0.91	14.39	0.68	13.74	1.32	-	-	10.53	-1.91
Tamana	17.10	0.33	17.45	0.92	14.12	0.86	-	-	12.46	-2.32*
Couva	6.64	1.18	7.96	1.58	8.34	1.39	-	-	7.44	-2.68*
Mayaro	11.30	0.63	15.66	1.31	11.58	0.77	-	-	9.31	-2.41*

* Significant at the 95% level.
** Significant at the 99% level.

Further analysis of the annual and seasonal precipitation involving overlapping ten-year means was carried out. These overlapping means were compared with the mean of the whole period--1921-66. The results are shown in Table 12. In terms of the annual totals for Trinidad as a whole, only the decade 1942-51 shows a change that is statistically significant at the 95% level. This statistically significant difference did not show up in the previous analysis where the period 1941-50 was considered because the highest total rainfall (107.09 ins.) occurred in 1951. This re-emphasises the effect that an exceptional year can have on the mean of any period.

The dry-season rainfall (January-April) shows one decade (1942-51) significantly different at the 99% level, and the consecutive over-lapping decades spanning the period 1943-56 were all significantly different at the 95% level. It can be inferred from this therefore that the dry season rainfall of Trinidad showed a significant fluctuation in a positive sense in the period 1942-56 and another fluctuation in the negative sense in the period 1957-66. None of the overlapping ten-year means of wet-season rainfall totals reached the 95% level of significance.

A different picture emerges however, when sub-periods within the time series are compared with one another using the second method outlined earlier. It was decided not to use the ten stations used above, in order to limit this

[illegible]

TABLE 12

COMPARISON OF OVERLAPPING TEN-YEAR MEANS WITH THE MEAN OF 1921-1966 AND t VALUES

Annual					January-April					June-November	
YEARS	$\bar{x}_k$	$\bar{x}_k$	$-\tau_k$	t	YEARS	$\bar{x}_k$	$\bar{x}_k - \bar{x}$	τ_k	t	$\bar{x}_k$	t
1921-30	72.14	-3.83	-0.32	-1.33	1921-30	10.60	-0.93	-0.16	-0.55	50.65	-0.53
22-31	71.74	-4.32	-0.35	-1.25	22-30	9.90	-1.82	-0.31	-0.99	50.28	-0.72
23-32	71.86	-4.11	-0.34	-1.21	23-32	10.32	-1.21	-0.21	-0.73	49.53	-1.10
24-33	73.92	-2.05	-0.17	-0.60	24-33	10.51	-1.02	-0.17	-0.61	51.51	-0.10
25-34	72.14	-3.83	-0.32	-1.31	25-34	10.61	-0.93	-0.16	-0.55	49.53	-1.10
26-35	74.36	-1.57	-0.13	-0.47	26-35	10.67	-0.86	-0.15	-0.51	50.79	-0.46
27-36	75.53	-0.44	-0.04	-0.13	27-36	11.25	-0.29	-0.05	-0.17	51.17	-0.27
28-37	72.20	-3.77	-0.31	-1.11	28-37	9.79	-1.74	-0.30	-1.05	49.76	-0.98
29-38	74.00	-1.97	-0.16	-0.57	29-38	10.76	-0.77	-0.13	-0.46	49.78	-0.98
30-39	73.07	-2.90	-0.24	-0.85	30-39	10.84	-0.70	-0.12	-0.41	49.10	-1.33
31-40	74.34	-1.63	-0.14	-0.47	31-40	10.96	-0.57	-0.10	-0.34	49.92	-0.90
32-41	74.32	-1.65	-0.14	-0.48	32-41	10.92	-0.61	-0.11	-0.36	50.58	-0.57
33-42	74.88	-1.09	-0.09	-0.32	33-42	11.00	-0.53	-0.91	-0.31	50.76	-0.48
34-43	74.10	-1.87	-0.15	-0.54	34-43	11.60	0.07	0.01	0.05	48.95	-1.41
35-44	76.60	0.62	0.05	0.18	35-44	11.77	0.24	0.04	0.15	50.63	-0.54
36-45	77.32	1.44	0.12	0.39	36-45	12.47	0.93	0.16	0.57	51.12	-0.29
37-46	77.69	1.71	0.14	0.50	37-46	12.55	1.02	0.17	0.62	50.79	-0.46
38-47	78.82	2.85	0.24	0.83	38-47	13.58	2.05	0.35	1.25	50.76	-0.48
39-48	76.67	0.70	0.06	0.20	39-48	12.63	1.09	0.19	0.66	50.70	-0.51
40-49	77.77	1.79	0.15	0.52	40-49	12.42	0.89	0.15	0.54	51.40	-0.15
41-50	80.31	4.33	0.36	1.28	41-50	13.73	2.20	0.38	1.35	52.49	0.39
42-51	83.88	7.91	0.65	2.44**	42-51	16.03	4.50	0.77	2.95**	52.78	0.54
43-52	81.97	6.00	0.50	1.80	53-52	15.02	3.48	0.60	2.20*	52.67	0.48

TABLE 12 continued:

	Annual					January-April				June-November	
YEARS	$\bar{x}_k$	$\bar{x}_k$ -	τ_k	t	YEARS	$\bar{x}_k$	$\bar{x}_k-\bar{x}$	τ_k	t	$\bar{x}_k$	t
1944-53	81.68	5.71	0.47	1.71	1944-53	14.46	2.92	0.50	1.82*	52.78	0.53
45-54	81.55	5.57	0.46	1.66	45-54	14.60	3.07	0.53	1.92*	52.63	0.46
46-55	81.83	5.85	0.48	1.75	46-55	14.44	2.91	0.50	1.81*	53.19	0.74
47-56	82.07	6.10	0.50	1.83	47-56	15.23	3.70	0.63	2.35*	53.23	0.76
48-57	81.07	5.10	0.42	1.51	48-57	13.91	2.37	0.41	1.46	53.38	0.84
49-58	81.39	5.42	0.45	1.61	49-58	13.70	2.17	0.37	1.33	53.22	0.76
50-59	79.67	3.70	0.31	1.09	50-59	13.45	1.92	0.33	1.17	52.47	0.38
51-60	78.30	2.32	0.19	0.68	51-60	12.27	0.74	0.13	0.45	52.30	0.30
52-61	74.01	-1.96	-0.16	-0.57	52-61	9.96	-1.57	0.27	-0.95	51.67	-0.02
53-62	74.03	-1.95	-0.16	-0.57	53-62	10.15	-1.38	0.24	-0.83	51.84	-0.06
54-63	72.77	-3.20	-0.26	-0.94	54-63	9.90	-1.63	0.28	-0.99	51.56	-0.07
55-64	73.05	-2.92	-0.24	-0.85	55-64	9.84	-1.70	0.29	-1.02	52.06	-0.18
56-65	72.32	-3.65	-0.30	-1.07	56-65	9.90	-1.63	0.28	-0.98	51.01	-0.35
57-66	72.08	-3.89	-0.32	-1.14	57-66	8.90	-3.63	0.45	-2.32	51.93	-0.11
1921-40	73.24	-2.70	-0.22	-1.35	1921-40	10.78			-0.75	50.28	-1.21
1921-50	75.60	-0.38	-0.03	-0.29	1921-50	11.77			0.37	51.02	-0.91
1921-60	76.27	0.30	-0.03	0.42	1921-60	11.89			1.08	51.34	-0.92

* Significant at the 95% confidence level.
** Significant at the 99% confidence level.

section to manageable proportions, but to take one representative station from the different change régimes that emerged from the analysis of cumulative percentual deviations from the means of annual and seasonal rainfall totals. The Trinidad case was used as a representative of one of these change régimes and the St. Madeleine's case as representing the other. A summary of this analysis is given in Table 13. The

TABLE 13

COMPARISON OF MEANS OF SUB-PERIODS AND VALUES OF t

STATION	SEASON	PERIODS COVERED	t VALUES
Trinidad	Annual	1921-30 with 1941-50	2.26
		1921-40 with 1941-50	2.43
		1929-38 with 1956-65	2.65
		1947-56 with 1957-66	-2.40
	Dry	1921-30 with 1941-50	1.87
		1921-40 with 1941-50	1.39
		1929-38 with 1956-65	2.17
		1941-50 with 1957-66	2.54
		1947-56 with 1957-66	2.53
	Wet	1921-40 with 1941-50	1.18
		1934-43 with 1944-53	1.40
		1941-50 with 1957-66	2.67
St. Madeleine	Annual	1925-34 with 1940-49	0.73
		1930-39 with 1940-49	1.25
		1939-48 with 1949-58	1.78
		1947-56 with 1957-66	2.62
	Dry	1921-30 with 1931-40	0.79
		1925-34 with 1935-44	0.96
		1930-39 with 1946-55	1.20
		1939-48 with 1949-58	2.20
		1947-56 with 1957-66	2.38
	Wet	1929-38 with 1939-48	1.87
		1936-45 with 1947-56	1.25
		1945-54 with 1955-64	1.28
		1946-54 with 1955-64	1.78

short term oscillations that are prominent in the graphs of percentual deviations from the mean are lost sight of in the long period smoothing, and, relative to the period 1921-66 as a whole do not seem to be statistically significant. However when individual oscillations are compared, the fluctuations in the short period are sufficiently numerous and significant to be of interest. Of four comparisons made between the differences in means of sub-periods for annual rainfall in Trinidad all were significant at the 95% level (Table 13) although only one (1947-56 compared with 1957-66) reached that level of significance at St. Madeleine. In a previous analysis where the relationship between the mean of the sub-period and that of the whole period was considered, no statistically significant change was shown to have occurred. For the dry season, three comparisons of sub-periods showed significance at the 95% level in the Trinidad data as against two at St. Madeleine. While for the wet season only the period 1941-50 compared with 1957-66 for Trinidad was significant.

This section of the analysis does two things. Firstly, it supports the earlier findings that the period 1957-66 was significantly different at both rainfall seasons when considered in relation to the whole period (1921-66), and when compared with other sub-periods. Secondly it confirms a point that was made earlier about the fact that fluctuations in a climatic time series may be statistically significant

in relation to one another although becoming insignificant when considered in relation to the whole series. Increases or decreases in the mean values of climatic elements when compared over individual fluctuations may show differences, over the period covered by these fluctuations, which are in fact significant, yet these significant differences may disappear in any long term statistical analysis. But what length of period is to be considered sufficiently long to be statistically valid? Certainly, ten years is a long enough period for any significant fluctuations in climatic elements or a climatic element to have some impact on the environment.

The use of different methods to investigate the possible fluctuations and trends in the rainfall of Trinidad was a conscious effort to indicate the difficulties that may arise in these widely used methods especially in terms of statistical significance. Fortunately, the series used here were relatively normally distributed, but the problem would have been greatly aggravated if the series were highly skewed. Also, these analyses raise the question, whether each of the monthly values of rainfall should be individually examined for trends and fluctuations in areas where the rainfall is characteristically seasonal. One thing seems to be certain, and it is that one must be very cautious in drawing conclusions about changes and fluctuations in rainfall when only annual values are considered.

It can be established then that there have been

fluctuations in the rainfall of Trinidad, West Indies, during the period 1921-66; also established is the fact that these fluctuations are of an average length of eight to ten years. In addition it is seen that the fluctuations, when considered as a whole over the period under review, seem to cancel out and therefore show no statistically significant changes in the rainfall pattern of the period or no marked trends. As has been indicated the fluctuations have variances that are significantly different from one another. In the opinion of the writer, these fluctuations, while not being sufficiently persistent either in the positive or negative sense to establish a definite trend, are of sufficiently long duration to be of local consequence. The recurrence intervals of the oscillations in the rainfall series are not sufficiently regular to be cyclic, yet those of eight to ten year duration, and the shorter ones of from four to five years seem to be of a persistency that can bear further investigation. This is taken up later.

CHAPTER V

VARIANCE SPECTRUM ANALYSIS OF PRECIPITATION TIME SERIES

The normal variability that exists in the precipitation records suggests that still further statistical verification should be attempted if the evidence of fluctuations or periodicities in this element is to be relied upon. Further analysis is therefore attempted in this chapter. Much "cycle" research has been undertaken in an empirical fashion with the hope of first obtaining statistically significant results and, if possible, of tying these to some plausible physical causes. Most of these studies used some form of harmonic or periodogram analysis (Berlage, 1954; Brier, 1954; Abbot, 1958; Angell and Korshover, 1963; Eliasen, 1958; Horn and Bryson, 1960; Sabbagh and Bryson, 1962; Yen and Dotson, 1969). A review of the findings which are based on reasonably adequate statistical procedures reveals as the most universal rhythms or osciallations the following: 2·3, 3·3, 5-6, 11-12, 19-24 and 30-35 years in length (cf Landsberg, 1957).

Panofsky and McCormick (1954) have pointed out that direct harmonic analysis yields a number of harmonics equal to half the number of observations; that the amplitude of these harmonics oscillates widely from one harmonic to the

next and finally, that the oscillations are not reproducible from one time series to another which has basically the same statistical properties. Therefore, there is a need to compute a smooth spectrum. The autocorrelation method with the number of lags small compared to the number of observations yields a smooth spectrum directly with a great deal less numerical work than would be required for computing and smoothing the spectral estimate obtained by direct fourier analysis.

Tukey (1949) has indicated that the autocorrelation function $C(\tau)$ should be applied to the "normalized" autocovariance function because its value for lag zero is unity. The autocovariance function which is the covariance between $x(t)$ and $x(t + \tau)$ as a function of lag τ is quite useful although more difficult to interpret than the variance density spectrum. Wiener (1930) showed that the variance spectrum (i.e., the decomposition of the variance with frequency or scale) and the autocovariance function contained the same information about the data. Subsequently, it was shown by Tukey (1949) and independently by Bartlett (1950) that the variance spectrum has a more stable distribution and that statistical confidence bands may be easily calculated. Tukey has also argued (1949, 1959a) that the variance spectrum is more easily interpreted than the autocovariance.

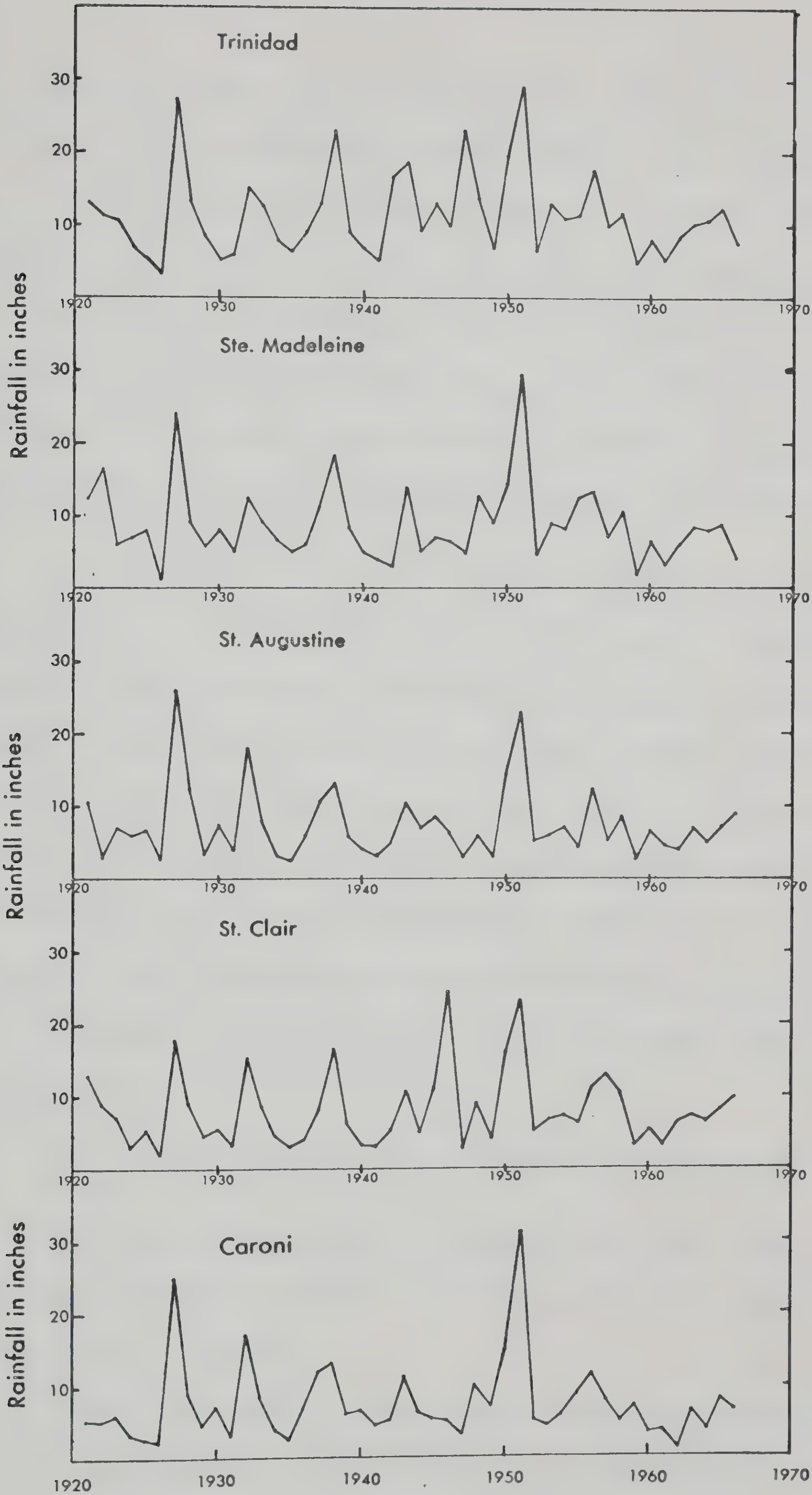
Blackman and Tukey (1958) have claimed that

"as a means for understanding, and as a guide for

> intelligent design, the variance spectrum is without a peer. The autocovariance function is of little use except as a basis for estimating the power spectrum. This is fundamentally because, in most physical systems power spectra have reasonable shapes, are relatively easily understandable, and are often quite directly influenced by the basic variables of the situation, whatever these may be."

For time series of rapidly fluctuating elements, variance spectrum analysis has become a widely accepted technique to separate "signal" from "noise". In meteorological series this tool has been primarily used for phenomena such as turbulent wind fluctuations and transfer of heat and momentum (Busch and Panofsky (1968), Chiu Wan Chang (1960), Estoque (1955), Panofsky and Deland (1959). It has gradually found its entry into analyses of wave motions on a hemispheric-synoptic scale (Boville and Kwizak, 1959; Eliasen, 1958), climatology (Fitzpatrick, 1964; Rayner, 1965, 1967; Sabbagh and Bryson, 1962; Horn and Bryson, 1960;) and hydrology (Rodriquez Itube, 1967). The method will be applied here to the analysis of the Trinidad precipitation series, 1921-66.

The starting point in this spectral analysis is a function of time, x(t) defined in an interval $0 \leq t \leq T$ in years relative to an arbitrary origin, 1921. The time series x(t) exhibits apparently widely fluctuating properties to the eye, and in previous sections of this work was shown to have oscillatory properties that can be isolated. Plots of some of this time series (graphs of x(t) against time t) are shown in Figure 29. They represent the dry season rainfall



Mean Dry-season rainfall of Trinidad -1921-66, for five stations

Figure 29

for five stations in Trinidad between 1921 and 1966 inclusive. Time series of annual rainfall were also used.

Most meteorological elements are notable for "persistence" in the short period, but since the element dealt with here is precipitation over intervals of one year, and for intervals of one season per year, it is assumed that the errors have a common but generally unknown distribution, the variability of which is characterized by its variance:

$$\sigma^2 = E(x-\mu)^2 = \int_{-\infty}^{+\infty} (x-\mu)^2 p(x)dx \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (8)$$

where $E(x) = \mu$ is the mean value of x which is assumed to be constant and $p(x)$ is the probability density function of the errors. Since the errors are Gaussian, the μ and σ^2 characterize the distribution completely. Again, since $x(t)$ is a function of time another factor is considered because consecutive values of $x(t)$ are correlated. Therefore in addition to μ and σ^2, the simplest multivariate moment namely the covariance between the values of $x(t)$ at different times need to be specified;

$$\gamma_{ij} = E\{(x_i-\mu)(x_j-\mu)\} = E\{[x(t_i)-\mu][x(t_j)-\mu]\} \ldots (9)$$

and since the assumptions of approximate stationary and near normality are made, then μ, σ^2 and γ_k provide complete descriptions of $x(t)$.

The data used in this section are the same as were used in the earlier parts of this investigation viz., monthly precipitation. Monthly totals were summed over each twelve

months to give the annual precipitation and over four months--January to April inclusive of each year, to give the annual dry season total. The annual total rainfall for four stations--Trinidad, St. Madeleine, St. Augustine, and St. Clair over the period 1921-66, and the annual dry season totals for the same stations over the same period are the time series analysed. The computations were executed through a computer programme. There are forty-six discrete data points in each series, a number which is probably marginal in terms of the length of series for spectral analyses. There are no discontinuities in the data and as a whole the data series are homogeneous. It must be pointed out that modification or filtering of data frequently takes place although not always intentionally. The way in which the variable is recorded often modifies the data. The daily summation of rainfall, and then averaging over a month to give the mean monthly rainfall figure is such a form. In this case the daily summation of rainfall to give the monthly total effects a modification. The effect of these processes on the data is scale dependent.

Tukey's paper (1949) which deals with the sampling theory of power spectrum estimates, and his subsequent paper as co-author with Blackman (1958) form the basis of this analysis. The formulae given here are, in essence, those of Tukey with two exceptions: (a) the total overall mean is used to determine all serial products rather than the mean for the individual lag interval; (b) division of all

covariances by the initial covariance permits the immediate computation of normalized line powers. However, when the data are plotted in this form, the variance at zero lag is not readily available. The formulae used are as follows:

(i) Serial Products:

$$SP = \sum_{i=1}^{n-p} (X_i - \overline{X})(X_{i+p} - \overline{X}); \quad \ldots \ldots \ldots \quad (10)$$

$$\overline{X} = \left(\frac{1}{n}\right) \sum_{i=1}^{n} X_j \quad \ldots \ldots \ldots \ldots \ldots \quad (11)$$

where p is the lag and n is the number of observations in the entire series.

(ii) Mean Serial Product or Covariances:

$$R = SP/(n-p) \quad \ldots \ldots \ldots \ldots \ldots \quad (12)$$

(iii) Mean Lagged Product

$$C_r = \frac{1}{n-rh} \sum_{q=0}^{q=n-rh} X_q \cdot X_{q+rh} \text{ for } r=0,1,2,\ldots m \ldots (13)$$

where $mh<n$. It must be noted that so far as functions of C_r are concerned the effective folding frequency is $f_N^* = \frac{1}{2\Delta t} = \frac{1}{h} f_N$

(iv) Covariance Ratio:

$$R/R_o = R' ;\; R_p/R_o = R'_p ;\; o<p<m \ldots \ldots \ldots \ldots (14)$$

(v) Line Powers:

$$L_o = (1/2m)(R'_o + R'_m) + (1/m) \sum_{p=1}^{m-1} R'_p \quad \ldots \ldots \ldots (15)$$

$$L_h = (1/m)R'_o + (2/m) \sum_{p=1}^{m-1} R'_p \cos ph\pi/m + (1/m)R'_m \cos\pi h \quad \ldots (16)$$

$$L_m = (1/2m)(R'_o + (-1)^m R'_m) + (1/m) \sum_{p=1}^{m-1} (-1)^p R'_p \quad \ldots (17)$$

where m is the maximum lag $o \leq p \leq m-1$; $o \leq h \leq m-1$.

(vi) Smoothing formula (Hanning):

$\sigma^2(k)$ is modified to the form $\sigma_h^2(k)$ via

$$\sigma_h^2(0) = 0.5\sigma^2(0) + 0.5\sigma^2(1)$$

$$\sigma^2(1) = 0.25\sigma^2(0) + 0.5\sigma^2(1) + 0.25\sigma^2(2)$$

$$\sigma_h^2(k) = 0.25\sigma^2(k-1)+0.5\sigma^2(k)+0.25\sigma^2(k+1)\ldots k=2\ldots \ldots m-1 \quad (18)$$

alternatively, the case i = 2

$$V_\circ = 0.5V_\circ + 0.5V_i;$$

$$U_r = 0.25V_{r-1}+0.5V_r+0.25V_{r+1};$$

$$U_m = 0.5V_{m-1} + 0.5V_m \quad 1\le r\le m-1 \quad (19)$$

(vii) Line Variance:

$$\sigma^2(k) = \frac{1}{2m} \cdot 2 \cdot \{R(o)+2\sum_{\tau=1}^{m-1} R(\tau)\cos(\frac{\pi k}{m}\tau)+(-1)^k.R(m)\} \quad (20)$$

where k = wave number, τ = lag, $\sigma^2(k)$ = line variance

$\sigma^2(o)$ and $\sigma^2(m)$ are just half of the values given by the above formula. A crosscheck can be made however, by calculating R(o) from $\sigma^2(k)$ as follows:

$$R(o) = \sum_{k=0}^{m} \sigma^2(k) = 1 \text{ (because of normalization)} \quad (21)$$

Hanning was applied to the auto-covariance function through the variance spectrum sub-routine.

The choice of the maximum number of lags m is important in obtaining the spectral estimates (Griffith et al, 1956). It makes it possible to determine the variability of the data at a specific frequency. For resolution of the spectrum into narrow bands, m should be as large as possible, but if it is too large the computational work involved greatly

increases and more important, the accuracy of the estimates decreases. It is suggested that m should be small enough in relation to N to make the number of degrees of freedom satisfactorily large since the number of degrees of freedom is related to the number of lags and the number of observations by:

$$df = \frac{2N - m/2}{m} \quad \ldots\ldots\ldots\ldots\ldots (22)$$

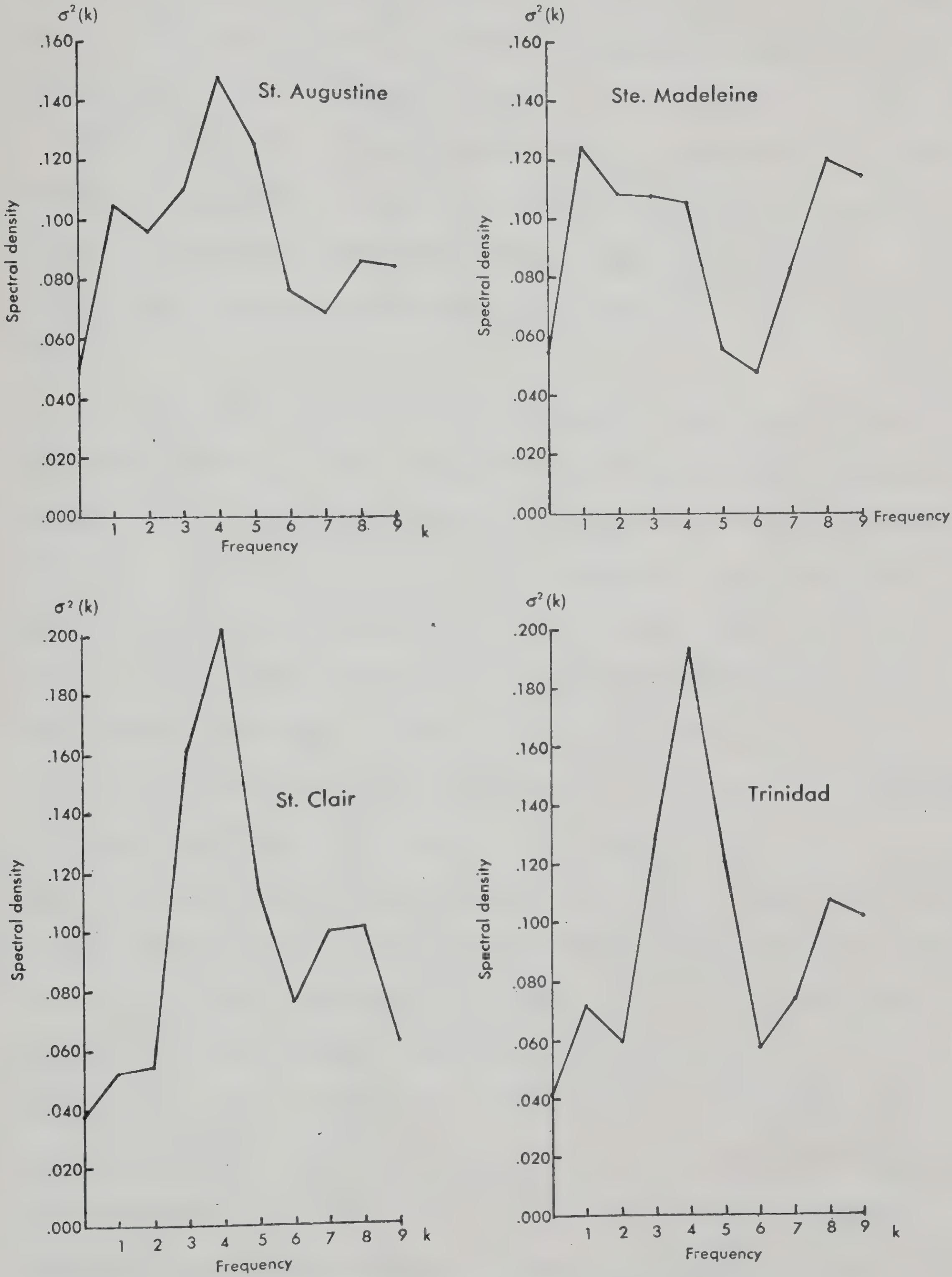
where m = number of lags used. Tukey (1958) suggests maximum lags in the vicinity of five to ten per cent of the length of the record; Jenkins and Bartlett favour twenty to thirty per cent. A maximum lag of ten years was used in this analysis because of the length of the record available. Spectral estimates with fundamental periods of $2m\Delta t$ are obtained for frequency bands centred at:

$$0, \frac{1}{2m\Delta t}, \ldots\ldots \frac{m-1}{2m\Delta t}, \frac{1}{2\Delta t} \quad \ldots\ldots\ldots\ldots\ldots (23)$$

The original data have been shown to be near normal and so the variations of the spectral estimates are expected to follow the Chi-square distribution (Panofsky and Brier, 1958). Hence peaks are tested to find whether they are meaningful or simply due to sampling variations.

RESULTS:

Normalized variance spectra of mean annual rainfall during the period 1921-66 for three stations within Trinidad and for the island as a whole are shown in Figure 30. The most prominent feature of these spectra is the five year



Normalized variance density spectrum of mean annual rainfall, 1921-66.

Figure 30

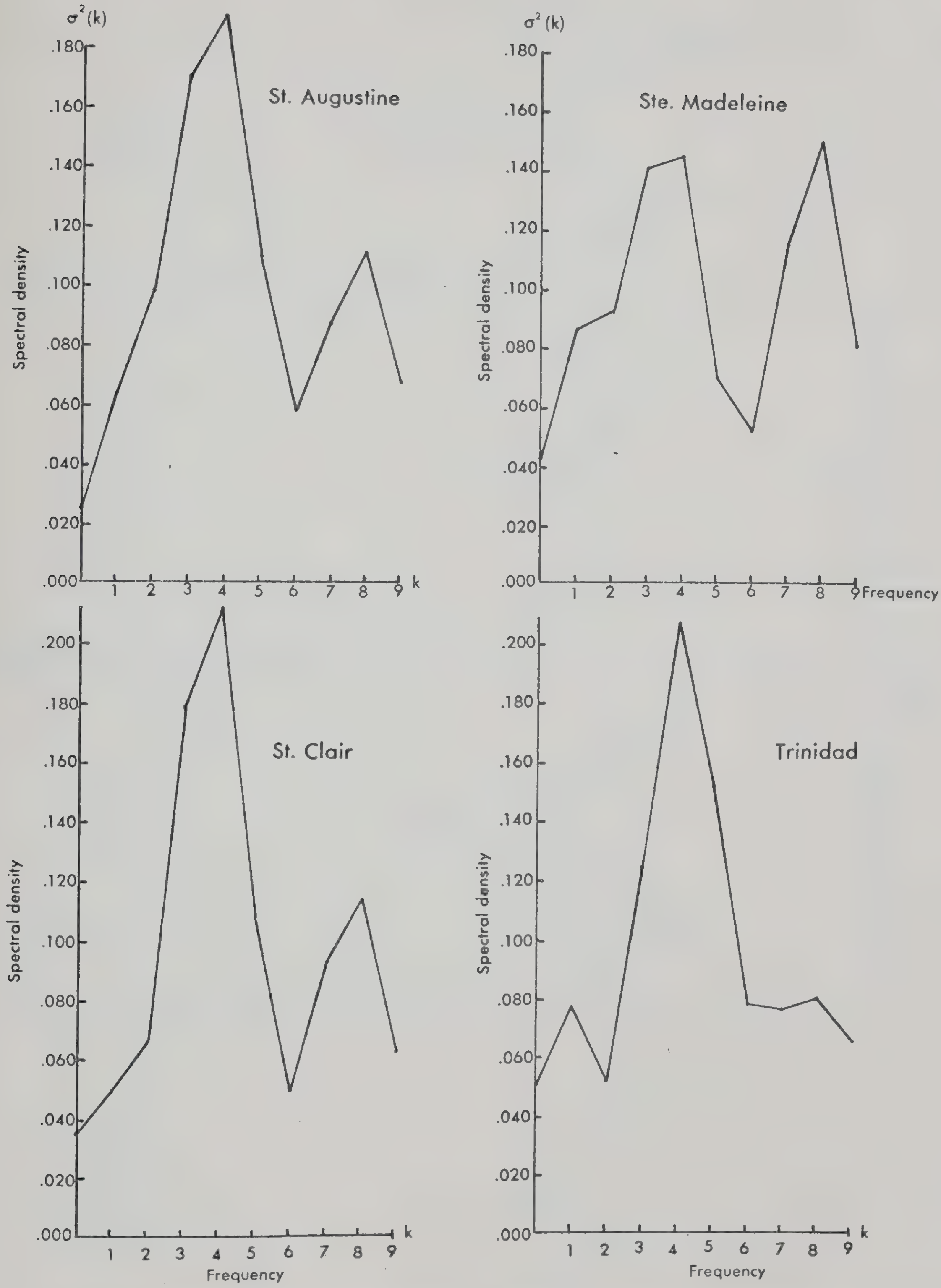
oscillation (f=4) that appears in three of the four curves shown. The peak at this particular frequency accounts for 20% of the total variance of annual rainfall for Trinidad as a whole, 21% in St. Clair and 15% at St. Augustine. At St. Madeleine, periods of 2.5 and 20 years (f=8 and 1 respectively) together account for 25% of the total variance. The twenty-year period contributing 13% and the 2.5 year period 12%.

The amplitudes of these spectral peaks were tested for significance. With variance spectrum analysis any frequency can be analysed independently of the number of observations. The use of ten year lags permits the finding of spectral estimates at frequencies 0, 1/20, 2/20, 3/20 up to 10/20. It is then possible to show the oscillations that are more highly probable. Since the original data have a near normal distribution, the variations of the spectral estimates are distributed as Chi-square. The choice of $m = 10$ in equation (13) gives eight degrees of freedom. The 5% limit of Chi-square is 15.51 and the 5% limit of the Chi-square/df is 1.78. On the assumption of white noise the theoretical estimate of the spectral amplitude at frequency = 4, for example is 0.096. Under the "white noise" assumption and a 95% confidence limit the expected spectral amplitude (relative variance) is 0.162 for $k = 4$. The variance actually associated with this spectral maximum (five year cycle) is 0.195 for Trinidad, 0.203 at St. Clair, 0.149 at St. Augustine but only 0.106 at St. Madeleine. The five-year peak

at St. Clair is significant at the 99% confidence level. At St. Madeleine neither of the two spectral maxima is significant at the 95% confidence level.

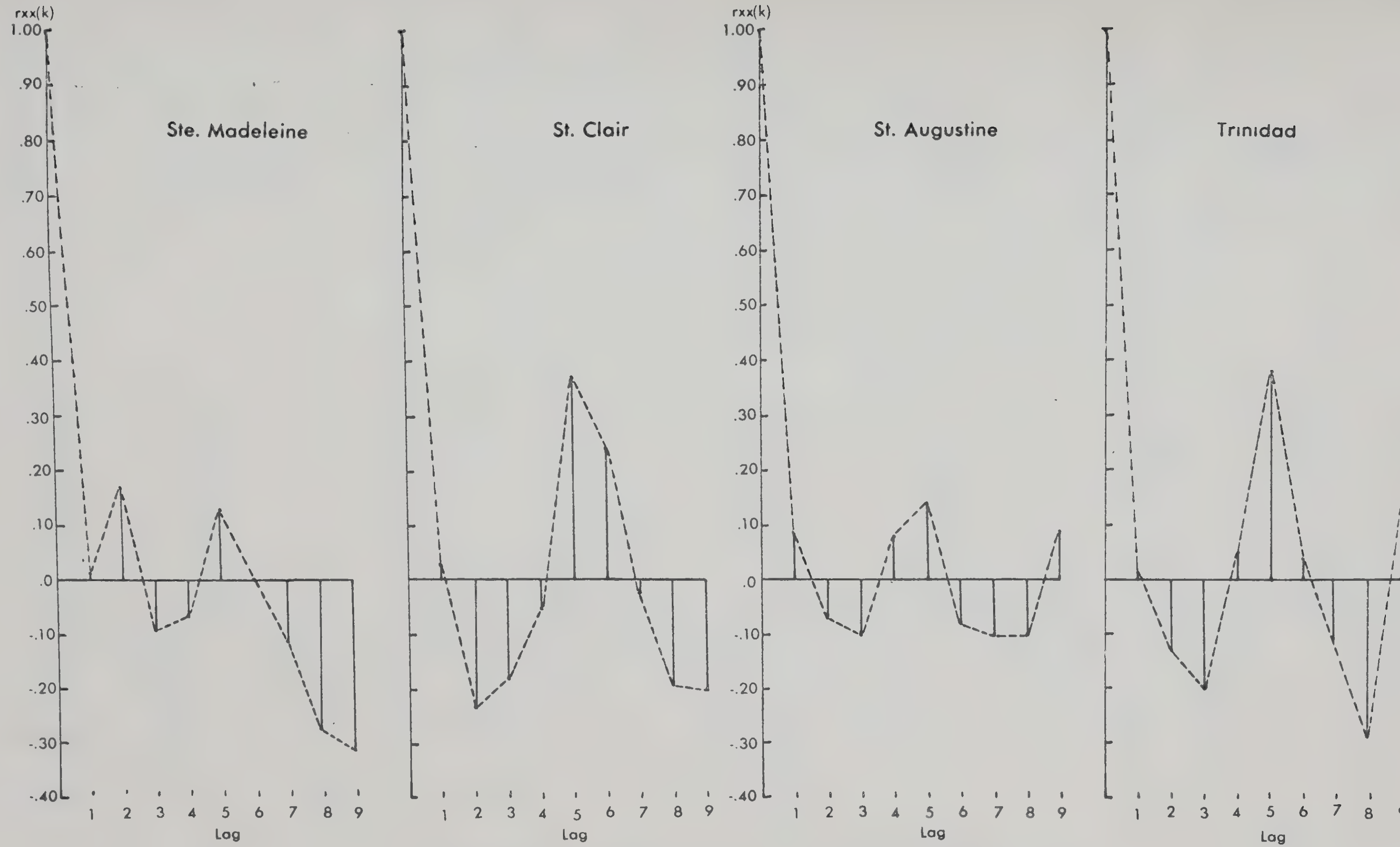
Figure 31 shows the variance spectra of dry season rainfall for the same stations over the same time period as above. The dry season picture is somewhat different. For Trinidad as a whole, the dry season rainfall exhibits two spectral peaks--one at a period of five years and the other near a period of four years. The former is significant at the 99% level, while the latter is significant at the 95% level. At St. Clair, the five year cycle is significant at the 99% limit, while the four year cycle is significant at the 95% level. The St. Augustine spectrum shows two prominent peaks. The one at five years is significant at the 99% level, while the other of around 6.6 years is significant at 95%. There are three peaks in the St. Madeleine spectrum which together account for 44% of the total variance--6.6 years (14.2%), 5 years (14.5%) and 2.5 years (15%). None of these however, quite reaches the 95% confidence level.

Figures 32 and 33 which show the auto-correlation functions of annual rainfall and dry season rainfall respectively lend support to the variance spectra although no test of significance is available for indicating the importance of the peaks shown therein. The secondary peak at about a period of 2.5 years (lag 8), although not statistically significant in any of the spectra occurs at all stations for both the dry season rainfall series and the annual rain-



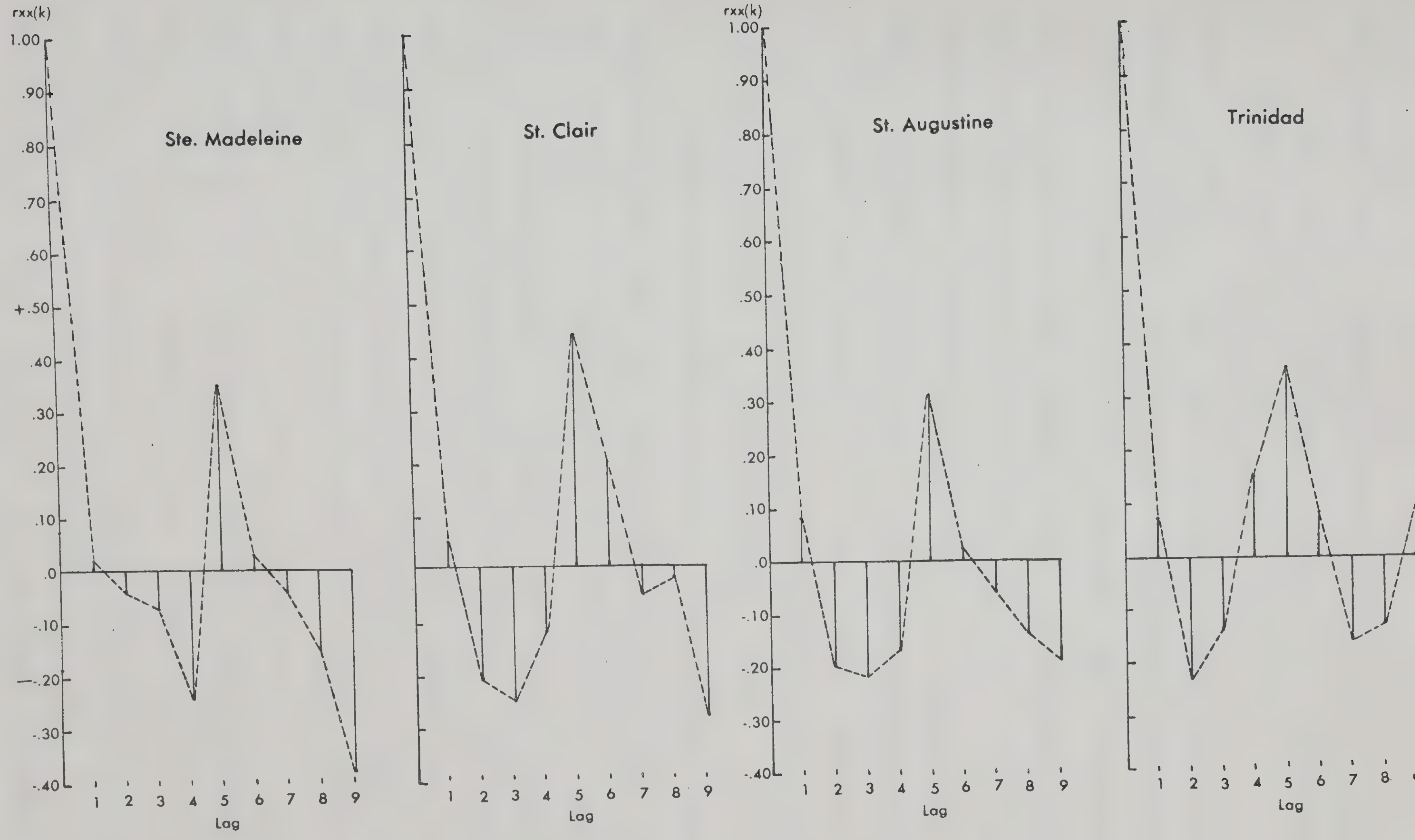
Normalized variance density spectrum of mean dry season rainfall ; January-April,(1921-66)

Figure 31



Normalized autocorrelation functions of mean annual rainfall,1921-66.

Figure 32



Normalized autocorrelation functions of mean dry season rainfall, 1921-66

Figure 33

fall series with a relatively high correlation coefficient.

The most prominent oscillations in the annual rainfall series of the stations analysed were 4, 5, and 6.6 year periods. These periods were not equally important at all stations. However, the five year oscillation was highly significant at almost all stations tested. The same periodicities show up in the dry season rainfall series and again the five year period was statistically significant at all stations except St. Madeleine where there is evidence of a 2.5 year and a twenty year period. These periodicities of four and five years may probably be of some unique interest, because their interpretation might very well be essentially meteorological rather than astronomical.

It must be emphasized that a single sample sequence can produce many different spectra depending upon the various filters and windows used in the calculations. Nonetheless a spectrum provides a different and often extremely revealing way of looking at a sample sequence. The same information is contained in the original data as the spectrum but is arranged differently. Therefore any one spectral analysis should be considered as one of a number of possible alternative steps in the process of investigation. It is not necessary that any spectral analysis should provide concrete results but it should at least suggest new lines of inquiry. The data analysed in this section show certain dominant oscillations with periods of about 2.5, 4, 5, 6.6, 20 years, and these might very well be time scale dependent. In

addition, the processes that generate these oscillations may have different physical causes. The variance spectrum gives some indication as to the scale of these generating processes and may therefore suggest lines of further investigation.

Finally, there is a need to indicate that even though large and quite regular variations occurred in the precipitation of the period under study, it is quite possible that equally large and regular variations with the same oscillatory periods may not repeat themselves in the next forty-five year period. For example, in Figure 29, the striking oscillations evident in the period 1925 to 1945, were not reproduced with the same intensity in the period 1950 to 1965. However, the earlier oscillations (1920 to about 1950) dominate the variance distribution sufficiently to imprint their basic characteristics on the spectrum. This is not to deny that the period after 1950 did not contribute to the variance, but its contribution was perhaps much less than that of the earlier period. Consequently, extrapolation into the future using this technique must be guarded.

CHAPTER VI

CORROBORATIVE EVIDENCE FOR CLIMATIC FLUCTUATIONS

The statistical analyses in Chapters IV and V show that fluctuations exist in the precipitation of Trinidad with what appears to be a certain regularity. It was hinted in Chapter IV that it might be possible to assess the significance of, or obtain corroborative evidence for these fluctuations by using other methods and approaches. Two such approaches will be given here: (a) the water balance approach and (b) the dendroclimatic approach. Water balance computations and tree-ring data are used in an attempt to seek confirmation of the fluctuations in rainfall. These two have been chosen because any fluctuation in precipitation should be readily reflected by both of them.

(a) The Water Balance

Precipitation has always been considered an important element in the hydrologic cycle. Within the past twenty years however, it has come to be assessed less for its totals and spatial distribution than for its effectiveness as soil moisture in the ecosystem. This approach has been heightened by the resurgence of evapotranspiration as a climatic element. Precipitation is seen as a supplier of moisture to the earth's surface. This moisture will be dissipated in various ways:

evaporation back to the atmosphere, percolation through and retention by the soil, run-off over the soil surface, interception by the leaves and branches of plants, and so on.

If the sufficiency and effectiveness of precipitation are to be measured in relation to the balance that exists between it as an input source of moisture, and evapotranspiration which should be taken as an output source of moisture from the earth surface, the concept of a "water balance" is valuable and effective. The idea of a water balance is a relatively new one which is tied physically to the concept of the "energy balance" through the concept of evapotranspiration.

One of the basic difficulties encountered in this concept arises from the problems in measuring evapotranspiration. The theory of turbulent diffusion cannot be applied to the realities of evaporation off natural surfaces until the dependence of evaporation on soil and vegetation factors is adequately defined. There is still no simple physiological theory of the transpiration process, or of the relation of soil moisture tension to total moisture content and the behaviour of the root system. In other words, the component parts of the natural evaporative process are not yet satisfactorily within the grasp of simple theory. Attempts to resolve this difficulty have resulted in a variety of approaches among which are: the aerodynamic approach, the energy balance approach, empirical formulae and in-situ measurements. The aerodynamic approach is based on the physics of vapour transfer by eddy diffusion; the energy budget

approach takes into consideration the fact that a knowledge of net radiation permits an estimation of potential and actual evapotranspiration. The in-situ measurement approach makes use of drainage lysimeters and evaporation pans. The practical empirical approach combines the energy balance approach with that of the aerodynamic in order to find equations that exclude normally unmeasured quantities. The resultant equations show that potential evapotranspiration is a function of the net radiation and a wind dependent saturation deficit term. One of the criticisms of this approach however, is that the wind function in the saturation deficit term is derived from an open water surface whereas vegetation covers are considerably rougher (Businger, 1959).

Empirical formulae relating evapotranspiration to meteorological data have been developed by a number of people among whom are Penman (1948, 1956) and Thornthwaite (1948). Numerous researchers have attributed advantages to one or other of these in various tropical regions (Chang et al, 1963, 1966; Fitzpatrick and Stern, 1965; Fuhriman and Smith, 1951; Cowan and Inness, 1956; Campbell et al, 1959; Yates, 1964; Thompson et al, 1966). The one that has been most widely used among geographers is that of Thornthwaite. His procedure of deriving the potential evapotranspiration from screen air temperature records has an obvious advantage in that this climatic element is the most commonly measured everywhere. It is conceded however, that air temperature represents only a limited measure of the energy exchange. The Penman formula

has not come into very common use because of the problem of data availability. The parameters used are not widely measured and therefore it is only over relatively small, intensely instrumented areas that the method can be effectively used. In most tropical regions stations that measure elements such as short wave incoming solar radiation, saturation vapour pressure at air temperature, actual hours of sunshine, horizontal wind speed at two meters height are almost non-existent. This makes the application of the Penman formula impossible for any sizeable geographic region. The Thornthwaite formula on the other hand, uses elements that are widely measured and it has been found to give comparable results (Bernard, 1945; Chenery and Hardy, 1945; Hardy, 1947; Sanderson, 1950). Furthermore, apart from providing a relationship between temperature, day length and precipitation and potential evapotranspiration, the Thornthwaite procedure permits a bookkeeping method for the calculation of actual evapotranspiration (ET.), surpluses, deficits, and run-off on the assumption that the value of soil moisture storage is known. Discussion of evapotranspiration estimations in the tropical regions shows the lack of agreement reached so far by using empirical formulae.

Cowan and Inness (1956), using the formulae of Blaney and Criddle, Thornthwaite, and Penman describe experiments in the tropics dealing with the application of meteorological data to the evaluation of evaporation from a free water

surface and the evapotranspiration from a continuous canopy of sugar cane in Jamaica, West Indies. The correlations between the derived estimates of evaporation and measured evapotranspiration as they calculated them are given in Table 14. They inferred from this that estimates based on

TABLE 14

CORRELATIONS BETWEEN EVAPORATION AND ESTIMATES OF EVAPORATION, JAMAICA, WEST INDIES

	r	r^2 x 100*
Penman	0.985	97
Blaney and Criddle	0.859	74
Thornthwaite	0.788	64

*r^2 x 100 is the per cent extent to which derived estimates agree with measured estimates.
(Taken from Cowan and Inness, 1956)

temperature data alone are far from precise under Jamaican conditions which may well be the case in many tropical maritime climates where the annual range of temperature is small. However, the ratio of measured evapotranspiration (E_T) to the Penman estimate derived from open water evaporation, E_o, seems to vary from 0.57 in Jamaica to 1.71 in Australia, and Thompson (1965) claims that results from an experiment in Natal show that measured E_T approximately equals Class A Pan evaporation. Tabulated "f" factors relating potential evapotranspiration of sugar cane to open water evaporation as estimated by Penman's E_o, obtained from studies by

Fuhriman and Smith (1951), Cowan and Inness (1956), Campbell et al (1959), Thompson et al (1963), Chang et al (1966) and Yates (1964) are given in Table 15. These data seem to indicate that the consumptive use of water by sugar cane, water

TABLE 15

MAXIMUM RATES OF POTENTIAL E_T, "f" FACTORS AND ESTIMATED E_o, FOR VARIOUS COUNTRIES

REGION	E_T measured ins./day	"f"	E_o (Penman) ins./day
Puerto Rico	0.19	0.95	0.20
Jamaica	0.15	0.57	0.26
Hawaii	0.34	1.30	0.26
South Africa	0.24	1.06	0.23
Queensland, Australia	0.36	1.71	0.23

not limiting, can be approximated with a Class A Pan, and that the ratio of evapotranspiration to pan evaporation lies between 0.9 and 1.7.

It is evident to this writer that there is some correlation between the consumptive use of water by, say, sugar cane and pan evaporation, but the wide variation of "f" factors reported seems to indicate that no basic generalization is yet valid.

Evaporation measurements have been made at St. Augustine since 1950. However, the evaporation pan used was not of the generally accepted standard, nor were the

records reliable until 1967 when U.S.W.B. Class A Pans were installed at a number of stations in the island, including St. Augustine (Figure 1). Some monthly values for 1968 and 1969 taken from the Piarco records are given in Table 16. These open pan values represent the maximum or potential evaporation E_o, that can take place from a free water surface under the prevailing climatic conditions. Evaporation in nature however, might be considerably less than the potential evaporation. Another source of water, that stored in the soil must be taken into account. The number of interrelated climatic and edaphic factors, and the innumerable combinations into which these factors may enter pose a formidable barrier to any simplistic approach. It is not impracticable however, to use the evapotranspiration concept and the water balance approach to indicate in the most general terms what the water requirements of an area might be, the periods in which deficits and surpluses are most likely to occur and with what regularity. For reasons already cited, the Thorthwaite method is used here to analyse the data available on the island of Trinidad.

Actual calculations of the water balances were effected through a computer programme, GEO ϕϕϕ1, a modification of "Silviculture General Utility Library Programme, GU-101 (Black, 1966). The programme is designed to compute the water balance by methods based on Thornthwaite and Mather (1957). The computations represent a "running tally" in

TABLE 16

CLASS A PAN EVAPORATION AT PIARCO, 1968 and 1969. (Values in mm.)

YEAR	JAN.	FEB.	MAR.	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1968	172.6	182.4	214.1	179.3	189.5	168.6	191.5	152.6	162.8	165.3	153.9	153.4
1969	144.0	175.3	256.5	252.9	256.5	135.1	184.1	166.8	160.8	151.1	138.2	139.7

which each year's water balance is calculated and the pertinent values from one year are carried over to the next. A summary follows the last year and represents monthly averages for the specified "categories" of the water balance.

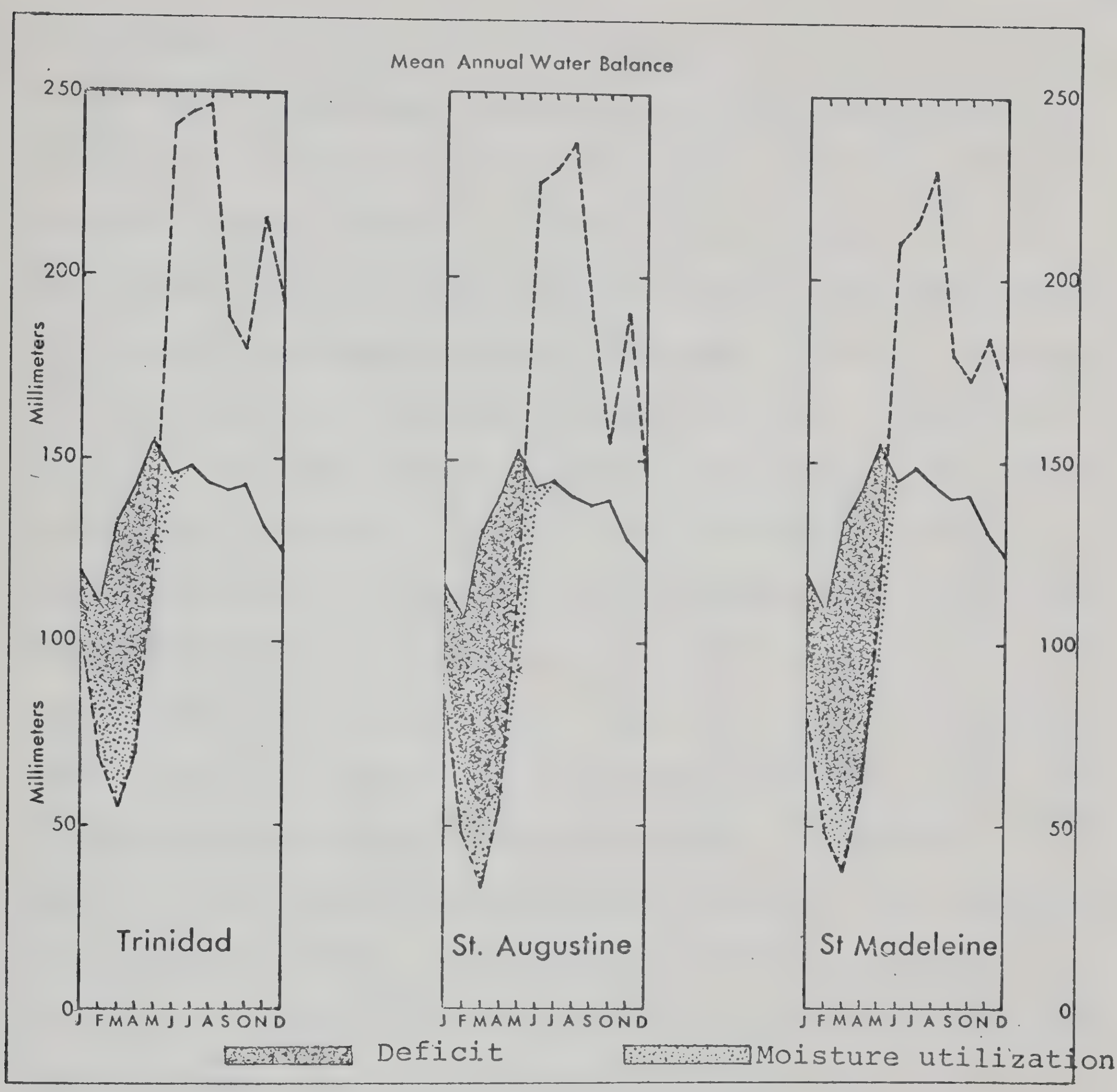
For the purpose of this analysis the storage capacity of the soil is fixed at four inches (101.6 mm.)(Thornthwaite and Mather, 1957) for two stations--St. Madeleine and St. Augustine and six inches (152.4 mm.) for the island as a whole. These values correspond to some estimates for tropical soils (Baver, 1942; Hardy, 1947; Terzaghi, 1942). There are of course important regional differences in the soils of Trinidad, and little is known about the water holding capacities of all the various soil types. Vegetation cover also adds to the complexity of the picture, for example, deep rooted crops such as tree-crops may increase the effective available water in the soil. For these crops ten inches (254 mm.) might be a more realistic value. Shallow rooted crops such as vegetables, on the other hand, reduce the available water in the soil. For these crops, three inches (76.2 mm.) might have been more correct.

If evaporation data were available for a larger number of stations within the island, the isolines of annual evaporation in Trinidad would probably show a constancy of form. In all months there is expected to be a general and rapid decrease of evaporation with increased distance from the coasts because of the combined effects of two factors:

convection and wind speed. Convection is strong over the land especially during hotter hours of the day when most of the evaporation takes place (Neuman, 1954; Pasquill, 1949), and is almost absent over the sea during that time. This increases cloudiness and reduces radiation overland. Wind speeds tend to be higher near the coasts than over inland areas. This is not only caused by more friction at the earth's surface but also by sea breezes which prevail during those hours when most evaporation takes place. Without further research it is impossible to say which of these two factors is more important in its effects on evaporation in the island.

Figure 34 shows the water balances for St. Augustine, St. Madeleine, and for the island as a whole based on long term averages of precipitation and temperature. The potential evapotranspiration values for St. Madeleine and St. Augustine are shown to be identical mainly because the temperature values used in the water balance computations for these two areas are the same. This is necessary because temperature data are not collected at St. Madeleine. The two areas which are about thirty-five miles apart are similar in terms of elevation, vegetation types and stage of economic development.

The water balance values based on long term averages at these two stations fail to show the effect of the year to year variability of rainfall, one of the important characteristics of precipitation in Trinidad. Figure 34 does indicate



Mean Annual Water Balances (1921-66) for Three Stations

Figure 34

however, that annual water deficits can be quite considerable even using long term means--314.5 mm. (12.4") in St. Augustine, 302.2 mm. (12.0") in St. Madeleine and 180 mm. (7.1") for the island as a whole. These deficits occur primarily in the period January to May. A secondary,

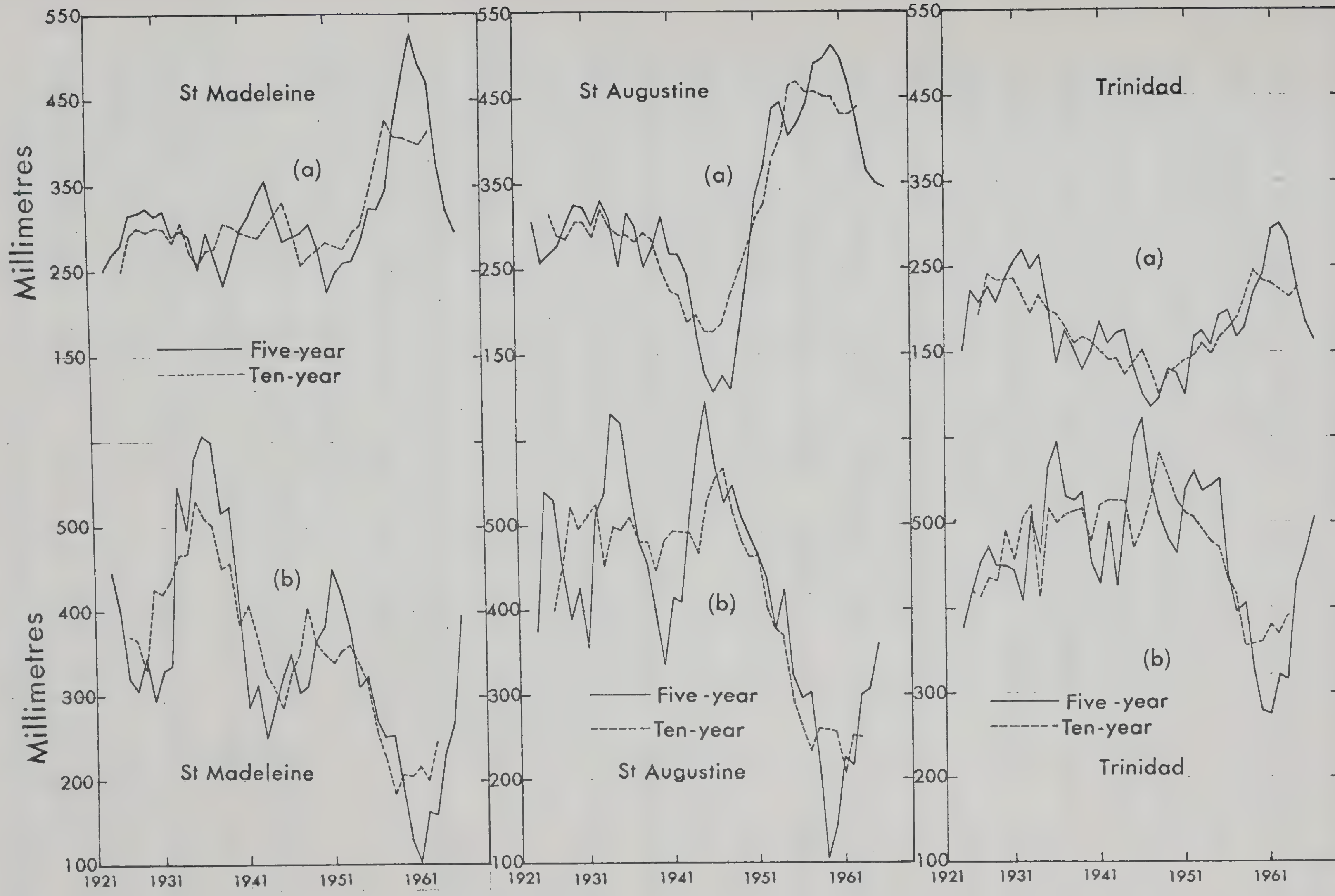
though minor deficit, that is known to occur in one or more of the months September to November of some years is not brought out. A general feature of these long term water balances (those calculated on the basis of means for the whole period) is that the potential evapotranspiration decreases when the precipitation increases. This is caused by the higher relative humidity (Figure 4), lower temperature and more cloudiness during times of rain as compared with dry periods. However, the variation of evapotranspiration is much smaller than that of precipitation. St. Augustine for instance, has values of monthly means of hourly relative humidity for January to April of 82, 80, 78 and 78% respectively while the values for June through October is 86% rising to 87% in November, returning to 86% in December. In addition, the relatively higher wind speeds in the dry season increase evaporation. The average wind speed in the dry season is 6.1 knots, but decreases to 4.5 knots in the rainy season (Figure 4).

The mean annual deficit for the forty-six year period (1921-66) at St. Augustine is 314.55 mm. (12.4"). The actual values range from 651 mm. in 1959 to 22 mm. in 1933 (25.6" to 0.9"). At St. Madeleine the mean annual deficit is 303.2 mm. (12"). The range is 722 mm. in 1929 to 25 mm. in 1922 (28.4" to 1"). The mean annual surpluses are 361.3 mm. (14.2") and 431 mm. (16.3") for St. Madeleine and St. Augustine respectively. These values are in themselves very revealing, but

it is probably more useful to obtain some indication of the variability of moisture sufficiency, trends and fluctuations in moisture deficits, and the regularity with which periods of large deficits recur.

Five and ten-year cumulative means of annual moisture deficits and surpluses were calculated for St. Augustine and St. Madeleine, and for the island as a whole. The curves are shown in Figure 35. At St. Madeleine, annual moisture deficit fluctuated considerably between 1921 and 1948, but there was an overall rising trend. This coincides with the period in which temperature was rising. There was a sudden rise in the values of moisture deficit between 1950 and 1960, and a decrease after this period. The period of sudden increase in the deficit values of the 1950's matches too the period of decreased precipitation. The graph of moisture surplus shows three periods of decreasing surplus and three periods of increasing surplus. Moisture surplus decreased in the periods 1921-29, 1935-42 and 1950-60, and increased in the periods 1930-34, 1943-49 and 1961-66.

At St. Augustine, moisture deficit fluctuated between 1921 and 1945, showing a generally decreasing trend. In the period 1945-59 however, there was a rapid increase in moisture deficit. This period was followed by another decrease. Moisture surplus on the other hand fluctuated widely, increasing in the periods 1931-34, 1940-45 and 1957-66 and decreasing in the periods 1922-30, 1935-39 and 1946-56. When



Five and ten-year cumulative means of:(a) annual water deficit and (b) annual water surplus - 1921-66

Figure 35

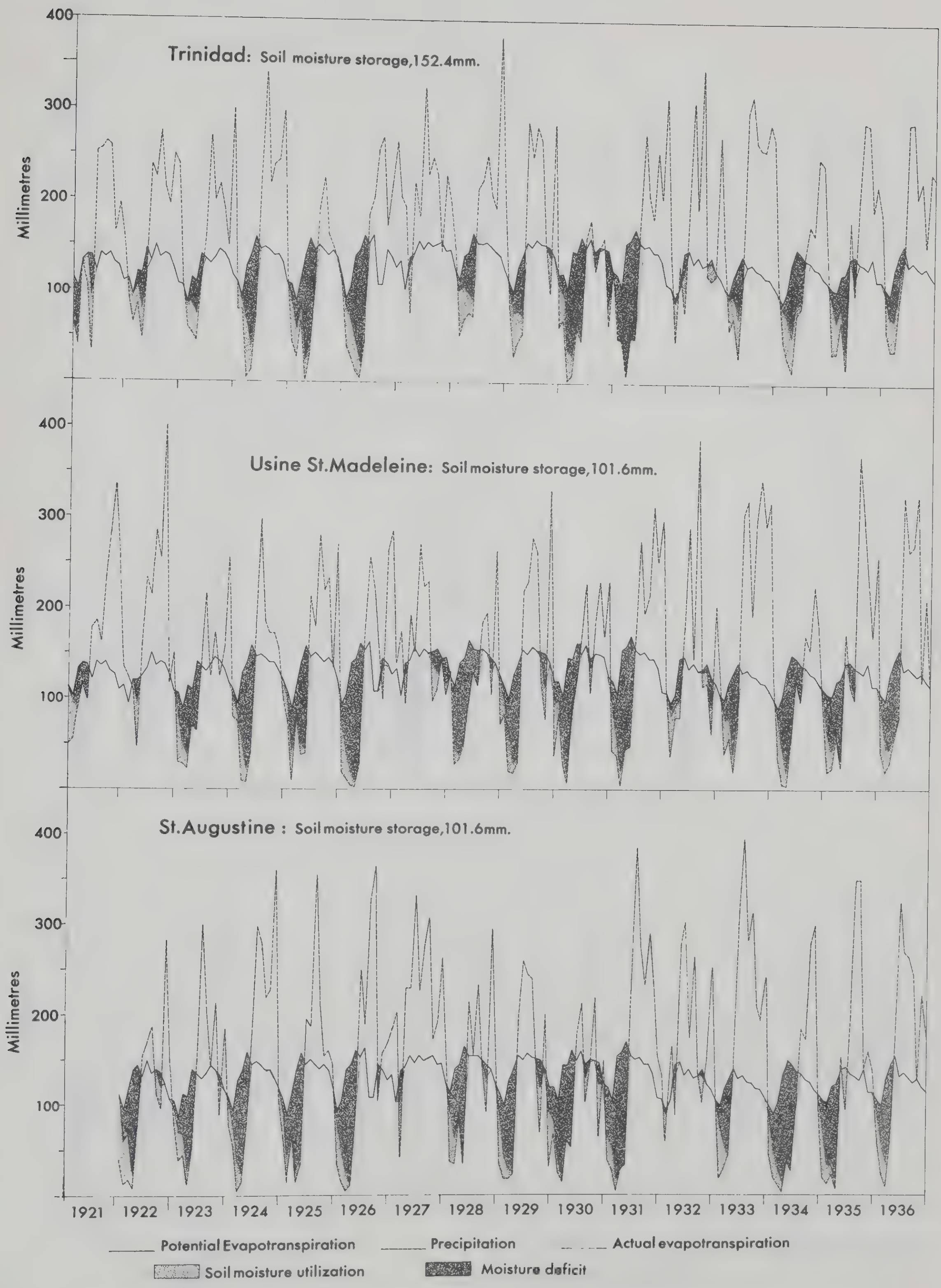
St. Madeleine is compared with St. Augustine some important differences can be isolated. In general the amplitudes of the major fluctuations are much greater at the latter station. In the period 1950-1960, the amplitude of the fluctuation at St. Madeleine was 305 mm. (12") while at St. Augustine it was 400 mm. (15.8"); also the periods of lowest deficits were different at both stations--1951 at St. Madeleine, but around 1945 at St. Augustine. Again, water deficit increased markedly at St. Madeleine from about 1951 to around 1960, and then decreased. At St. Augustine this period of marked increase in moisture deficit started around 1946 and continued to around 1961, before the decreasing trend started again--a lag of about five years. At St. Madeleine, the moisture deficit values fluctuated markedly between 1921 and 1951, but no major trend is noticeable; at St. Augustine however the short period fluctuations are present but a marked decreasing trend set in about 1933 and continued to about 1945. The fluctuations in the moisture deficit values are quite nearly coincident with the fluctuations in the dry season rainfall (see Figure 24).

For the island as a whole, the short period fluctuations are more marked--4-5 years in both graphs, yet it is possible to detect a decreasing trend in moisture deficit between 1921 and 1948; a rise thereafter to about 1962, followed by another fall. The graph of moisture surplus seems to indicate a widely fluctuating but rising trend between

1921 and 1946; a falling trend between 1947 and 1961 and a rise thereafter. As would be expected, there is a very close association between the graphs of moisture surplus and those of mean annual rainfall. Similarly, there is a close correspondence between the graphs of moisture deficit and those of mean dry season rainfall.

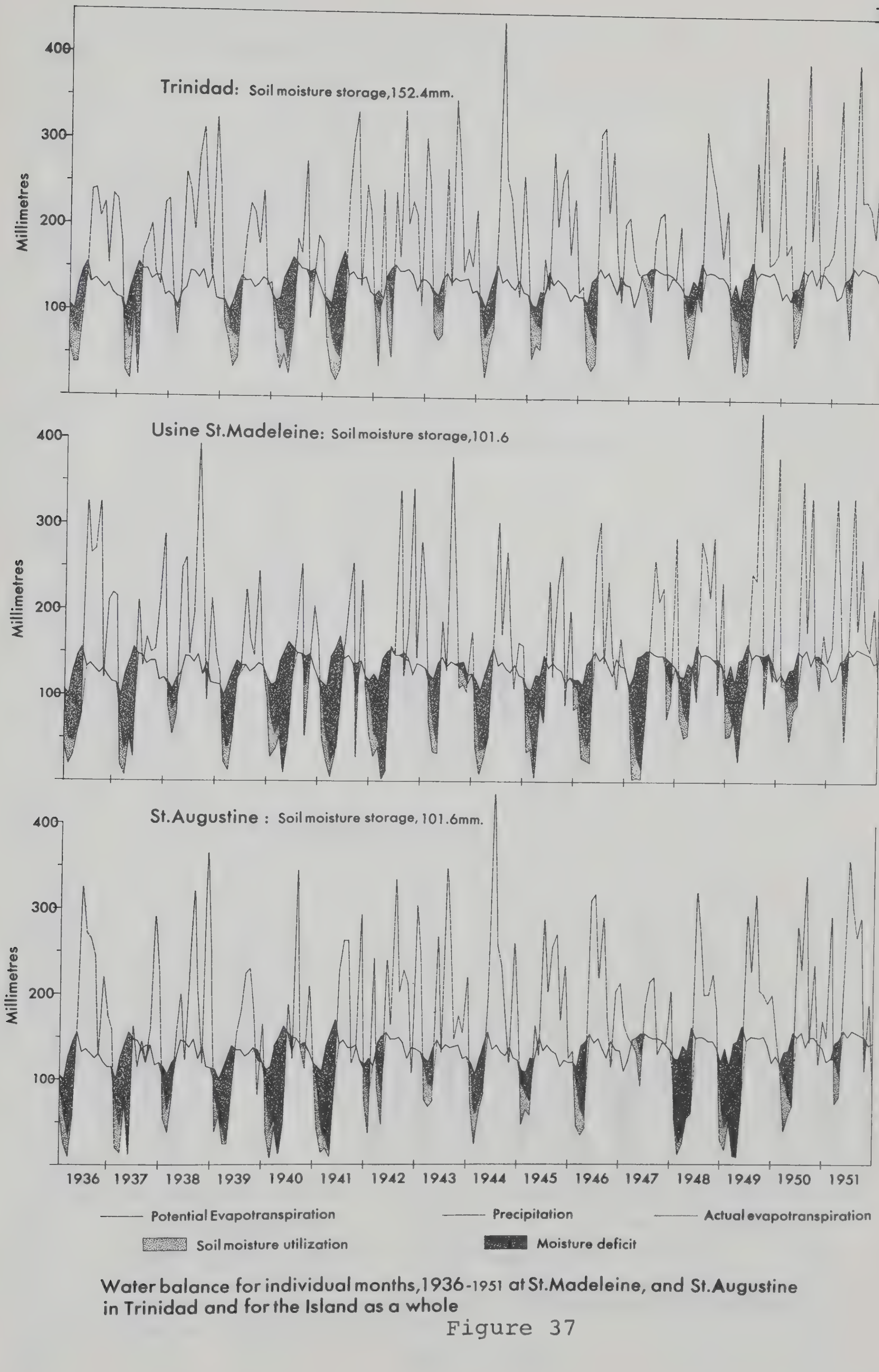
The influence of rainfall variability on the water balance is shown in Figures 36, 37 and 38, where the water balances are drawn for individual months for two stations and for the island as a whole over the period 1921-66. These water balances indicate that there is a considerable water deficit between February and June. Its magnitude is shown in Table 15. In exceptionally wet or exceptionally dry years, the duration of the period and the amount of water deficiency is quite variable. There are however, definite periodicities which correspond to the oscillations in rainfall. These periods are discernible on the graphs. There are two periods --one of five years duration in which an average of four years of relatively large moisture deficits (≈400 mm. or 15.8") is followed by one year of very low deficit value (≈77 mm. or 3"). Superimposed on this is a longer period of about eleven years.

The years of low moisture deficits seem to occur with predictable regularity--1922, 1927, 1932, 1938, 1943, 1948, 1951, 1956, 1961 and 1965. The longer period is no less marked (Table 17). There are a few exceptions. Time shifts



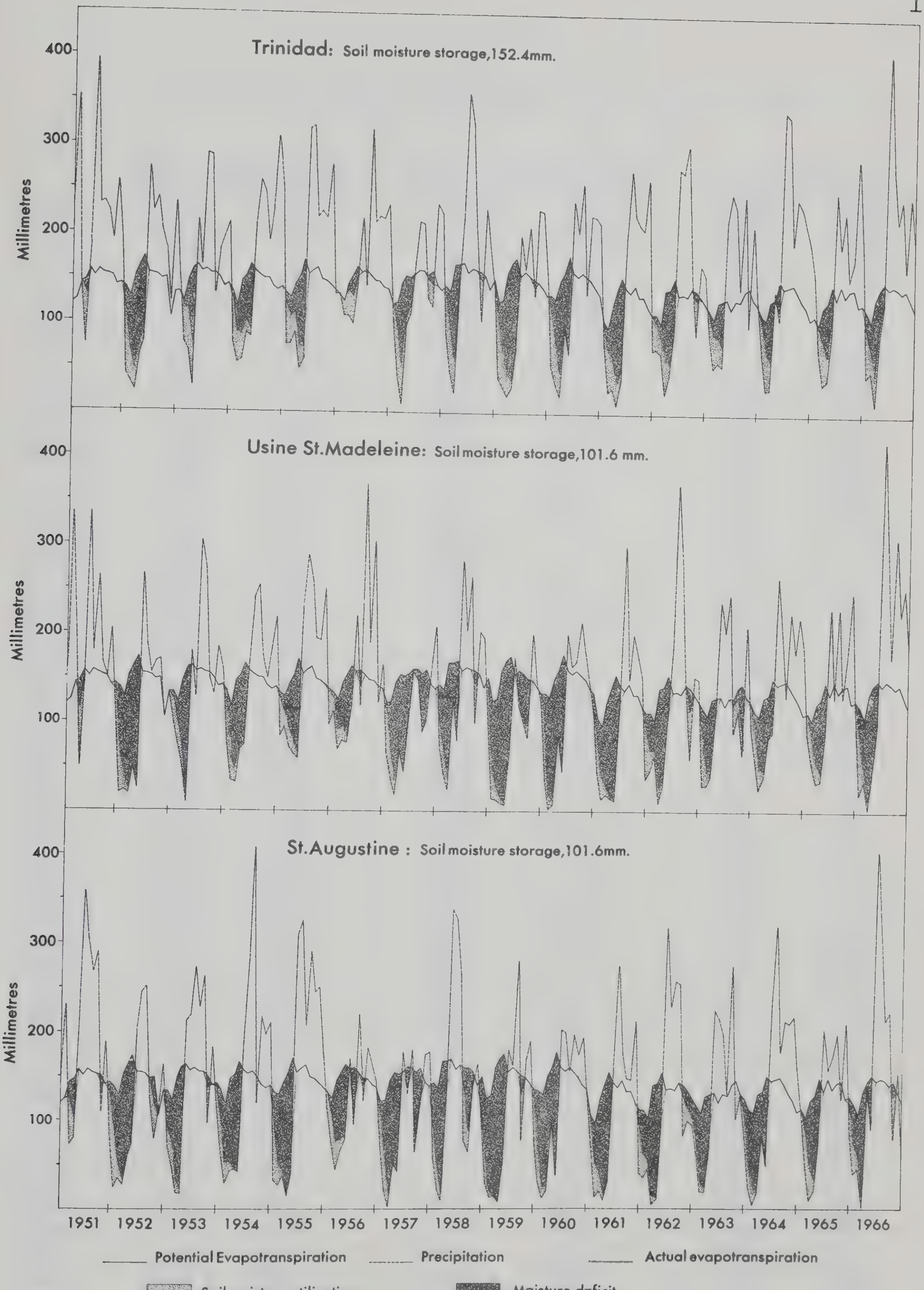
Water balance for individual months,1921-36 at St.Madeleine, and St.Augustine in Trinidad and for the Island as a whole

Figure 36



Water balance for individual months,1936-1951 at St.Madeleine, and St.Augustine in Trinidad and for the Island as a whole

Figure 37



Water balance for individual months, 1951 - 66 at St.Madeleine, and St.Augustine in Trinidad and for the Island as a whole

Figure 38

TABLE 17

ANNUAL MOISTURE SURPLUSES AND DEFICITS (mm.)
FOR THREE REGIONS (1921-66)

YEAR	St. Madeleine Surplus (mm)	St. Madeleine Deficit (mm)	St. Augustine Surplus (mm)	St. Augustine Deficit (mm)	Trinidad Surplus (mm)	Trinidad Deficit (mm)
1921	668	16	583	67	261	23
1922	756	25	149	279	602	80
1923	153	246	259	235	446	79
1924	204	318	613	298	573	240
1925	450	286	327	328	1	337
1926	431	482	533	395	484	375
1927	362	70	969	34	770	11
1928	71	415	208	285	532	160
1929	402	334	222	344	458	156
1930	199	311	16	455	0	468
1931	612	432	709	505	471	480
1932	396	107	623	22	585	29
1933	1130	204	1007	162	1034	103
1934	141	345	329	513	225	230
1935	619	300	483	339	515	193
1936	742	301	658	224	616	135
1937	374	320	251	341	266	208
1938	700	57	678	88	1010	3
1939	176	183	201	264	268	108
1940	91	476	172	447	102	294
1941	126	454	385	416	497	310
1942	474	404	630	126	615	83
1943	387	176	663	81	644	63
1944	347	270	696	153	666	124
1945	274	279	597	98	576	78
1946	298	288	648	182	615	149
1947	238	428	251	27	244	20
1948	427	201	432	164	464	110
1949	603	326	801	80	506	291
1950	339	129	423	444	492	61
1951	640	43	529	504	994	15
1952	91	542	135	467	339	365
1953	221	264	303	352	353	132
1954	260	328	497	421	538	212
1955	406	206	652	474	532	234
1956	369	219	21	307	437	44
1957	0	543	0	541	115	213
1958	226	375	340	467	404	190
1959	0	722	67	651	133	425
1960	52	517	104	494	300	333
1961	199	468	209	395	423	298
1962	333	374	411	457	344	245
1963	211	257	294	309	369	110
1964	366	269	482	410	710	140
1965	225	223	144	262	455	131
1966	832	359	470	311	651	190

are apparent between stations, hence slight variations in the actual years occur, but the periodicities are evident. It must be noted that in the period 1957-66, when both the seasonal and annual totals showed a sudden decline, the moisture deficits naturally became greater. The very wet year of any one period becomes less wet and so the disparity in moisture deficit between the four dry years and the fifth wet year that was so unmistakably present earlier became less pronounced although no less evident. It was in this period (1957-66) that some of the largest consecutive deficits occurred. A noticeable characteristic of the periods of high moisture deficits is the way in which the deficits are distributed. After a relatively wet year, the deficit builds up to a maximum which is reached on the fourth year as if in anticipation of the amelioration that the fifth year brings.

In some years there is a secondary deficit during the months of September, October and November, a feature of the water balance that is not apparent from the long term average graphs. The magnitude of the secondary deficit is relatively low ranging from 1 mm. to 70 mm. (0.04" to 2.8"). The largest of these secondary deficits occurred in 1957 when the deficits for September and October were 66 mm. and 70 mm. respectively at St. Madeleine and 69 mm. and 36 mm. at St. Augustine. There seems to be no recognizable pattern of occurrence for the secondary deficits,but after 1956 the values of moisture deficits have increased as have the

occurrences of secondary deficits.

The major period of water deficiency does not always coincide with the dry season except in years when December is exceptionally dry. The moisture stored in the soil, together with whatever rainfall occurs, is usually sufficient to meet the needs of evapotranspiration during the month of January, and to minimize the deficit in February. Deficits do in fact exist however, in the period February to June and sometimes July if the rainy season is late as it was in 1934, 40 and 57 for example, but the magnitude of the deficits increases rapidly after the complete utilization of soil moisture to a peak in June, after which time the rainfall is sufficient to meet the P.E. needs and to replenish the soil moisture storage. July is usually the month in which soil moisture recharge is at its highest.

The three water balances presented in Figures 36, 37 and 38 show remarkable similarities although the water balance for the island as a whole was based on the average values of precipitation and temperature from all reporting stations in the island. These of course include both areas of high rainfall and areas of low rainfall, but averaging over all stations only affected the magnitude of the deficits and surpluses. The other two balances will be commented on briefly.

The water balances for St. Madeleine and St. Augustine show that there is a considerable annual deficit in the

period February to June and in some years, July. The moisture is generally adequate during the remainder of the year to meet the P.E. requirements. In some years however, there is a minor moisture deficit in the period September to November caused by lower wet season precipitation as well as increased evaporation. This secondary period of moisture deficiency coincides with the second and deeper minimum in the sea level pressure curve associated with the sun's southward journey (see Figure 5). The largest surpluses occur in July, August and September. Although the water balance at St. Madeleine is very similar to that of St. Augustine, there is an important difference: the latter station shows larger surpluses and relatively smaller deficits. This is probably due to the fact that St. Madeleine is situated nearer the coast than St. Augustine. There is a definite periodicity of about five years in both balances. This periodicity is easily recognized on the water balances especially in the period 1921-57. After 1957 it is less easy to identify visually although it is still present. Superimposed on the high frequency period is a period of lower frequency.

In summary, it could be said that periods of water deficit occur annually in Trinidad and that the magnitude of these deficits depends on the variability of rainfall. The usual type of water balance based on long term averages fails to illustrate the important effect of short term rainfall variability. Month to month balances drawn for

individual years show considerable departure from the average conditions.

The largest moisture deficits occurred in 1959 when the actual values were 722 mm. and 651 mm. (28.4" and 17.0") at St. Madeleine and St. Augustine respectively. The total precipitation in that year was 1067 mm. (42.0") at St. Madeleine and 1250 mm. (49.2") at St. Augustine, while the dry season totals were 50 mm. and 63.5 mm. (1.9" and 2.5") respectively. The smallest deficit occurred at St. Madeleine in 1921 (16 mm. or 0.6") with a rainfall total for the year of 2034 mm. (80.1") and a dry season total of 308 mm. (12.1"), and at St. Augustine in 1932 (22 mm. or 0.9") when the annual total rainfall was 2065 mm. (81.3") and the dry season total was 450 mm. (17.7"). The largest surplus occurred in all areas in 1933--1130 mm. and 1007 mm. (44.5" and 40.0") at St. Madeleine and St. Augustine respectively. In June of that year a devastating hurricane struck the island. The total precipitation for that month was 301 mm. (12.0"). The smallest surplus values occurred in 1959 at both stations.

There are two unmistakable periodicities in the distribution of moisture deficits shown in the island--one of 5-6 years and the other of 11-12 years. Four years of large moisture deficit values are followed by one year of very small deficit. Superimposed on this is the period in which ten years of relatively large deficits are followed by one year in which a deficit that is even smaller than that of the

fifth year occurs. The isolation of these periods could undoubtedly prove invaluable to agricultural planning, irrigation schemes, and for the provision of water for both domestic and industrial purposes. In general, the fluctuations in the moisture deficits and surpluses shown in the water balance parallel those that appeared in the analysis of precipitation. The water balance analysis therefore confirms the conclusions of the rainfall studies.

(b) Tree-Ring Analysis

The statistical evidence presented so far indicates that rainfall and temperature fluctuations of a significant magnitude have occurred in the climate of Trinidad during the period 1921-66. Fluctuations in climate however, may also be assessed in terms of the biological effects observed. It seems useful to test the foregoing findings by analysis of data relating to plant responses. If plants reflect the fluctuations indicated by the previous analyses, these may be accepted as proof of the significance of these fluctuations.

The purpose of this section on tree-ring analysis is to see whether the fluctuations in climate in Trinidad are in fact reflected in tree growth. It is possible to test critically the covariation of growth and rainfall (Glock, 1955; Schulman, 1954), but in a preliminary investigation such as this, this method is probably too elaborate. This writer is aware of the short-comings and possible misinterpretation

inherent in (i) the use of rain gauge records taken some miles from the site of the tree samples; (ii) the use of a single radius to represent the entire volume growth of a tree and (iii) the emphasis on a single growth factor. However, if significant results are forthcoming in spite of these drawbacks by proper selection of trees from the correct habitat, this section will be worthwhile in view of the simplicity and directness of the approach. One is able to assume that the temperature factor, the other major climatic factor in tree growth will not be subject to such variability during the period as precipitation; hence assuming all other growth factors as unlimiting, fluctuations in growth rings may be taken as reflections of fluctuations in precipitation.

A basic assumption in tree-ring analyses is that the formation of a wide or narrow ring is largely a function of the available food supplies which are initially manufactured through photosynthesis and accumulated throughout the previous season; that climate influences ring growth primarily through its control of photosynthesis and other processes affecting the accumulation of stored food. However, climatic conditions can sometimes directly induce the cessation of growth. In the tropics, growth does not completely cease under certain limiting conditions, but may be retarded. Precipitation is the primary control, but temperature may modify its influence. Both elements affect the water relations of tree growth. Therefore, the ring widths represent an integration of the favourableness of the environment of

approximately one year's duration containing a dry season when water is scarce and a rainy season when the water supply is abundant. In tree-ring analysis it is inferred that the wider a ring the more moist the climate.

In 1970 four areas in Trinidad were chosen centering around four weather stations where relatively homogeneous rainfall records of long duration were available--Point Fortin, St. Madeleine, Couva and Tamana. These were selected as stations representative of the high rainfall areas (Tamana and Point Fortin) and the lower rainfall areas (Couva and St. Madeleine). In some years the western or leeward precipitation régime exhibits a major and a minor minimum, but the annual precipitation is always much lower than at the eastern or windward stations. The mean monthly distribution however, exhibits one maximum centering around the major plant growth season, May to December.

Several forest stands were sampled within a radius of three to four miles around each weather station. The samples were extracted from individual trees using a fifteen-inch Swedish Increment Corer. The trees sampled were dominant or co-dominant species and in the timber stage of development. Furthermore, the locations were chosen so that abnormal drainage toward or away from the trees was supposed to be at a minimum. When possible, several samples were taken from a variety of sites and species so that differences in the tree growth response might be compared. Five trees

were selected from each association. At first a sample of four cores from each of five trees was collected, but later a sample of two cores each from a larger number of trees was thought to be more representative of the regional tree growth pattern.

There were several problems ranging from the limited age of trees to the difficulty of locating species that would show pronounced growth rings. In cases where trees seemed old enough the trunks were so large even on apparently stressful locations, that the corer extracted a relatively short period of growth record. Because all cores consisted of apparently sound wood none was discarded. Furthermore, because site factors such as light, drainage slope, ground water relations and competition were evaluated on the site, no reason existed immediately after the collection had been made for the rejection of any specimen.

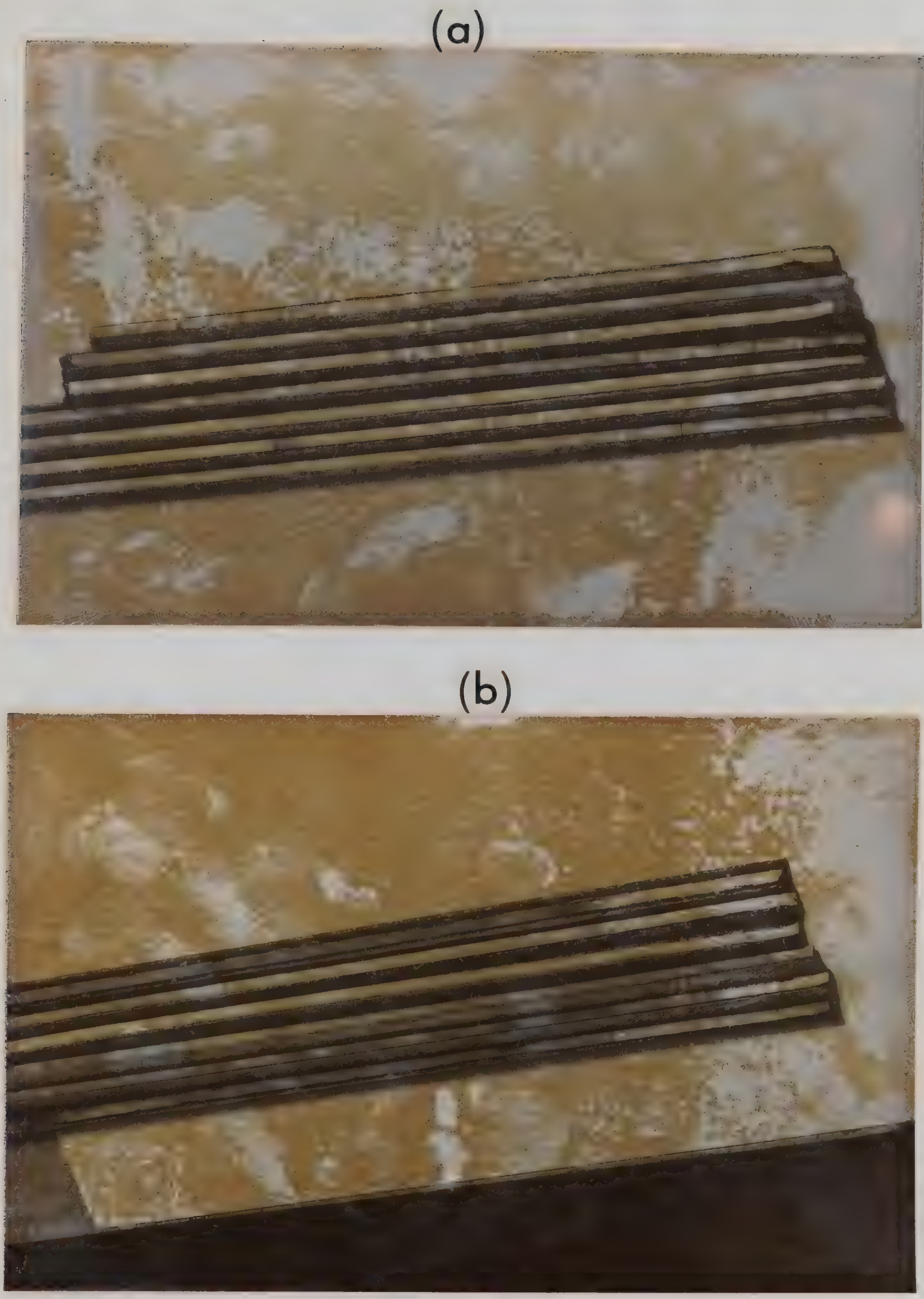
The cores were subjected to the following procedure to prepare them for analysis: They were air dried and then glued into a grove sunk into a wooden strip. They were then shaved and sanded to expose the growth layer (Carnegie Institute Publication, 1937). Beginning with the increment for 1970, the growth layers were counted inward and dated on the assumption that each sharply bounded layer represented a new initiation of growth. In effect, given normal conditions, a wide ring for the rainy season and a narrower ring for the dry season. In the case of the Jack-pine samples (<u>Pinus banksiana</u>) which were taken from a government operated

plantation (Forestry Department of the Ministry of Agriculture, Lands and Fisheries), the date of planting was also known. Skeleton plots were set up on co-ordinate paper, each ordinate representing a year. If a sharply bounded growth layer was decidedly narrower than its immediate neighbour an ink line was drawn on the ordinate appropriate to its date, the height of the line being inversely proportional to the thickness of the growth layer. The resulting skeleton plots are shown in Figure 39. Photographs of two sets of samples are given in Figure 40--set (a) showed growth rings set (b) did not. No actual measurements enter into the skeleton plots; the width relations were judged by eye.

On subjecting the samples to examination using both a low powered microscope and hand lens, it became evident quite early that the nature of the species is clearly more important than the influence of site. Only the samples taken from the pine forest showed any marked ring growth. Samples taken from various species of tropical hardwoods and softwoods, for example teak (*Tectona grandis*), mahogony (*Swietenia spp.*),Yellow savonetta (*Lonchocarpus punctatus*), and cedar (*Cedrela mexicana*) showed no recognizable growth ring differentiation. One other immediately noticeable phenomenon was the multiple growth ring per year. The trees seem to initiate growth more than once during the year, but the possibility arises that in a very wet year no break in growth might have occurred, and this tends to upset the time scale. It is

Skeleton plots of tree-ring samples.

Figure 39



Photographs of tree-cores: (a) those showing rings
(b) those that showed no rings

Figure 40

quite easy to circumvent this problem in an analysis or chronology based upon hundreds of specimens, so that it is easily known exactly when a ring is locally absent. Without these controls it is possible to "lose track of time" quite easily in a small sample, even in those samples for which both terminal dates are known--date of planting and date on which the sample was taken. Despite the large sample that was taken therefore, only a very small number was usable because of the difficulties outlined above. The wide variety of species in any one forest stand, and the marked tendency of most tropical species to show no definite growth rings impose grave limitation on the conclusions one can draw. It is with these limitations in mind that the results of the analysis are given.

An examination of the "skeleton plot" (Figure 39) reveals that there is no complete agreement among all the samples, however, there is sufficient agreement to enable certain general conclusions to be drawn. The majority of the samples confirm the decrease in rainfall amounts after 1956. All samples give evidence that 1959 was indeed the driest year of the period, and that 1951 was the wettest year of the tree-ring record. Previous rainfall analysis showed that 1951 was second only to 1938 for high water surplus. Unfortunately the tree-ring record does not go back that far. The tree-ring evidence supports the findings of the water balances indicating further that in the period 1940 to about

1954, sufficient water was available during the rainy season to produce relatively wide rings (shown by a "√" on the plot), and that the deficits were large enough to be manifested in relatively narrow rings. One notable disagreement exists between earlier findings and the tree-ring record for 1952. All the stations examined showed a large water deficit for that year (Table 17). However, all the tree-rings indicate a highly moisture deficient dry-season, but a rainy season with sufficient moisture to produce a wide ring. It may be noted though, that the station near which the samples were taken was not one of those used in the analysis of the water balance.

The periodicities in rainfall indicated in the variance spectrum analysis and again in the water balance analysis are not easily discernible in the skeleton plot of tree-ring data. Nonetheless, the effects of the seasonal distribution of rainfall on tree growth in Point Fortin, Trinidad are quite clear. In addition the marked reduction in the widths of growth rings in the decade 1955-65 both for the dry season and for the rainy season supports the earlier findings of a tendency to increased aridity during that period. Also, the ring widths seem to be associated closely with the magnitudes of deficits and surpluses as shown in the previous section.

The results obtained in this preliminary examination of tree-ring data seem to point to the fact that further

inquiry into dendrochronolgical evidence for climatic fluctuations in tropical regions could produce results that are meaninful and corroborative with respect to moisture fluctuations.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Trinidad like so many other countries in the tropics has not yet begun to appreciate the need for increased knowledge of its climatic resources despite the importance of these resources in its development planning. The climate of the island over the past forty-six years has not remained static. Analyses of the most relevant climatic elements have indicated that significant fluctuations have occurred and in some cases trends have become apparent. The fluctuations and trends were not identical at all the stations analysed nor were their temporal distributions exactly similar. Yet it is possible to make certain generalizations with respect to the magnitude, duration and significance of most of these fluctuations.

There have been fluctuations of irregular lengths in the temperature of Trinidad, superimposed on which was an increasing trend followed by a decrease. The rising trend started around 1933 and lasted until 1958, when a decreasing trend set in. The overall temperature increased by about 4.8°F. during the period of warming and decreased by about 3°F. during the period of cooling. There is however, no definite indication that there has been any significant

change in either the mean daily minimum or mean daily maximum temperature. Whatever changes there may have been, seem to have occurred simultaneously in the mean maximum, mean mimimum, and mean seasonal temperatures.

In the tropics, despite the changes and fluctuations in temperature which might have been noted in the first quarter of this century, temperature is not a limiting climatic element among climatic resources. If it is considered so, this is largely because of its role in the consistently high potential evapotranspiration rates. It is this feature of temperature therefore which makes precipitation the more critical and limiting among climatic elements in the tropics.

The methods used here to investigate fluctuations in precipitation have given results that are similar though not identical in terms of the exact years when phase shifts occurred. In most cases there have been lags which were not entirely unexpected as was explained in the section dealing with these methods. There is however, general agreement that not only has the dry season rainfall remained generally below the dry season mean for most of the period studied, but that there has been a tendency towards increased aridity in the period 1921 to around 1944 and 1957 to 1966. The decrease in precipitation after 1957 has been very steep at all stations examined. The wet season rainfall shows two major fluctuations which occurred on the average fifteen to twenty years apart. Within these major fluctuations and trends there are higher frequency fluctuations of four to six years' duration.

The results of the comparisons of means of different periods undertaken to show the statistical significance of fluctuations in precipitation indicate that most of the fluctuations isolated by the other methods failed to reach the 95% confidence limit when considered in relation to the whole period. When however, they are considered in relation to other fluctuations, they emerge as being highly significant. The statistical analysis gives confidence to make the statement that the period 1957 to 1966 was significantly different for both rainfall seasons both in relation to the long term mean and to other fluctuations. One general conclusion that can be drawn from these analyses is that the choice of method for the investigation of climatic fluctuations greatly influences the results obtained and that conclusions drawn from any one method must be guarded. No attempt was made to ascertain the correlation if any, that exists between fluctuations in the climatic elements or the degree of interdependence between any two of the variates. This might well form the basis of another study since it is probable that fluctuations in precipitation could, for example, be tied in with fluctuations in pressure or changes in the circulation pattern. In this regard co-spectrum, cross-spectrum and coherence-square analyses could be usefully applied.

From the studies on Trinidad (1921-1966) it is evident that there are fluctuations in precipitation. These fluctuations are apart from the normal variations that occur

in the distribution of precipitation. The analysis for the forty-six years studied shows that there might be a regularity in these fluctuations. It is information of this kind which must continue to be researched if the full value of the climatic régime is to be utilized. The late start that tropical regions have had in accumulating comprehensive data should no longer be allowed to be a hindrance to these studies. If action is to be taken with regard to the utilization of climate as a resource in the tropics, it is necessary to discover the patterns that exist in the fluctuations. For it is only if the variability of climatic elements in the long period is translated into some form of expectation that realistic forecasting and planning can be done.

Variance spectrum analyses of precipitation data have shown that certain basic oscillatory periods do exist in Trinidad. The most prominent oscillations in both the annual and dry season precipitation of the island are periods of 4, 5 and 6.6 years. These periods were not equally significant at all stations. However, the five-year oscillation was highly significant at the majority of stations tested. A notable exception is a 2.5 year period that shows up in the St. Madeleine data. These results have two important ramifications. Firstly, the greatest variances occur every five years in both the dry season and annual precipitation. In effect the expectation of a relatively wet year, or alternatively, a relatively wet dry season is given. On the basis

of this, it is possible to plan for the four relatively dry years with respect to water supply. The possibility exists that oscillations with the same periods may not repeat exactly in the next forty-six years, but it is equally true that in the field of climatology as in hydrology it is only by analysing the past that the future can be assessed on a probability basis.

Secondly, the scale of the oscillations points the way to further research. If it is accepted that the oscillations are real, it would appear that the mechanisms generating them might be meteorological rather than astronomical in nature. Therefore, any further investigation into the generating processes may very well be done with a basis in meteorology rather than with an eye to sunspots or such other phenomena.

It was argued in Chapter IV that while statistical analysis is important, the significance of observed fluctuations may be assessed from other points of view; consequently, corroborative evidence for climatic fluctuations were sought in the water balance and in tree rings. The analysis of the water balance confirms the significance of the five-year oscillation and indicated the same fluctuations in deficits and surpluses as were shown in the analysis of precipitation. It further shows that the deficit that occurs in the dry season of almost every year can be quite variable but always substantial, and points to the need for

irrigation during that season if enough soil moisture is to be available for plant growth. The deficits alluded to here relate to the plant-soil-atmosphere system and disregard for the moment the consumptive use of water for domestic and industrial purposes. If the latter is added the overall deficit becomes more significant. If the evaporation values recorded at Piarco during 1968 and 1969 (Table 16) are taken as measures of the evaporative power of the atmosphere under the prevailing climatic conditions, it is seen that the potential evapotranspiration or the basic moisture requirements of the island is, on the average 15.5 inches (395 mm.) during the dry season and 12.5 inches (318 mm.) during the rainy season. If during any one of these periods this amount of water is not available through precipitation a deficit exists. Further, when there is a diminution of total rainfall, there is invariably an increase in the potential evaporation or water need in the tropics. The mean dry season rainfall is 11.6 inches, indicating that in an average year the régime cannot meet the average water requirements of the dry season.

The water balance is a useful climatic indicator when used with reference to rainfall variability and the sufficiency of moisture in any region of the world. This is because of the role of evapotranspiration as one of its component parts. The evapotranspiration concept ties the water balance to the energy balance in a way that makes it feasible

to assess the water needs of a region if the energy input is known and if precipitation data are available. It is a concept that is universally applicable.

Increasingly it is being realized that economically there is a pressing need to utilize and develop climatic resources to the maximum. This is particularly true of the rainfall resources in relation to the water demands and economic activities of Trinidad's population. It is the spatial distribution of rainfall over the island which provides the primary water potential, but equally important are the changes in available amount with time. Exploitation and supply must necessarily be related to this, although actual developments may be controlled by a wide range of factors. In order to assess the role played by climatic conditions in producing and solving water supply problems in the island, it is essential that the relevant non-climatic conditions should also be considered.

The demand for water in Trinidad has increased considerably in the past thirty years. The rapid growth in population (a threefold increase), the tendency to urban expansion, and changes in agricultural techniques have all contributed to this increase. The actual use of irrigation on a major scale is at present limited but it is increasing rapidly in some areas especially in the truck-farming zones of the Caroni and Naparima plains. This automatically means an increased demand for piped water in rural areas for

agricultural purposes. In addition, domestic demands are steadily increasing as new houses with modern plumbing replace ill equipped older houses. The demand is further accentuated by the traditional use of the garden hose for watering and for washing of automobiles. Industrial demand continues to mount as Trinidad's manufacturing capacity increases and especially as the water consuming industries expand. Moreover, urban and industrial increases are not uniformly spread over the island. Rather, they are excessively concentrated into relatively limited areas which receive low to moderate rainfall, and in which the coefficients of variation are very high. The water shortage is thus accentuated by the concentration of high demands in relatively compact areas, the surrounding environment of which cannot cope with the demand.

On the supply side, the island must depend on precipitation directly, and on that part of the water surplus which may ultimately be harvested from underground sources or from surface flow. Surpluses are affected by atmospheric processes and by the variability of and fluctuations in precipitation in any given period, and it has been indicated that both seasonal and annual precipitation have fluctuated with what appears to be an organized regularity. The main source of supply therefore, is variable in amount and over time. The potential evapotranspiration demand, tied in as it is with the energy input remains, on the other hand, relatively

constant, so that, other things being equal, fluctuations in precipitation prove to be an important factor in water supply. In addition, changes in the surface characteristics of the island may adversely affect not only surpluses but also underground sources. Land use tendencies affect run-off rates, percolation rates and evaporation. The present tendency to deforestation attendent upon increased agricultural acreages and the drive to urban expansion with its concomitant increase in paved surfaces are two cases in point.

The final report of the Water Resources Survey (1969) emphasized the need for exploiting the ground water resources as an alternative source for urban and industrial areas on the grounds that a large supply is available and that its exploitation is more economical at present. While it can be argued that the exploitation of the underground sources will provide a supply that will be relatively reliable, and for a time at least, be free from the vicissitudes of climate, the surface changes referred to above will adversely affect the recharge rate of this source of water in the long run. It seems a more plausible proposition to face the realities of the dynamism of climate and take cognizance of the fluctuating and oscillatory nature of precipitation in any proposed plan for water supply in the island. The statistical techniques used to show the features of the climate of Trinidad over the past forty-six years should be applied again when more data become available for more stations over the country.

Hydrological studies which recommend the exploration of the underground sources on the basis of their relative economic cost at present must take account of those features of land use which may, in the long run, diminish the recharge of these sources.

The demand for water is increasing generally, and regional shortages are becoming accentuated, but there is no indication that the supply is increasing. The annual variations in precipitation are still in evidence and the variability of dry season rainfall is still very high. More important is the fact that over the past forty-six years there has been a tendency towards increased aridity during the dry season, although the wet season precipitation has been adequate for the water needs of the island during that season. In four years out of every five the climate is unable to satisfy the water requirements during the first five months of the year and in some years deficits show up in the period October to November. While population density was low, urban agglomeration limited both in number and in size, public health and sanitation negligible, and agricultural and industrial techniques poorly developed, it was possible for fairly adequate supplies of water to be obtained from local sources anywhere in the country--fluctuations in precipitation notwithstanding. As these factors have changed over the past fifty years, so the exploitation of the climatic resources for water has become more intensified and the areas for future expansion more limited. On the basis of the

information assembled in this study, dry season precipitation is always inadequate, and if the régimes of the past forty-six years repeat themselves in the future there will be groups of years in which the deficits will be very substantial. There is therefore a need for more studies as relevant data become available. These studies are important not only for a better understanding of the mechanisms of precipitation occurrence, but because the knowledge obtained can be used to offset any economic disappointments and for long term planning. It is now on the high rainfall areas of the uplands that the island must rely for its water supply. This implies that steps would have to be taken to increase storage facilities by planning the strategic location of reservoirs in areas where the demand is relatively low and transport the water to areas where the need for increased supplies is of immediate urgency.

It is quite possible that climatic fluctuations of the type discovered in the Trinidad data may also exist in the data of other islands in the West Indies. It is also possible that the islands so affected may be facing the same problems as Trinidad. While therefore, it is useful to investigate the climate of individual islands, it is likely that a regional approach to studies of this kind will be of immense value. They will make for a better understanding of the regional rainfall climate and may even provide some insights into the mechanisms operating to produce climatic fluctuations in that part of the tropical world.

APPENDIX

INDEX TO RAINFALL STATION

Hydrometric Area No.	Station	Location Lat. North	Long. West	Daily Records Start From	Monthly Records Start From	Discontinuity From	To
2:1	Tamana	10°27'51"	61°10'35"	1933	1923		
5:1	Mayaro	10°08'13"	61°01'00"	Oct.1927	Oct.1927	Jan.1945	June 1946
5:5	Moruga	10°05'07"	61°16'53"	1927	1910		
6:2	Point Fortin	10°13'10"	61°32'12"	1927	1910		
8:2	Couva	10°26'18"	61°28'56"	Feb.1927	1910		
8:13	St.Madeleine	10°15'37"	61°25'15"	1927	1910		
9:1	St. Clair	10°40'21"	61°30'54"	1927	1910		
9:2	Caroni	10°36'32"	61°23'55"	1927	1910		
9:32	Piarco Airport	10°35'14"	61°20'37"	1946	1946		
9:33	St.Augustine	10°38'13"	61°23'59"	1923	1923		

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